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Analytical Study of Residential Buildings With Reflective Roofs

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ABSTRACT

This report presents an analysis of the effect of roof solar reflectance on the annual heating (cooling) loads, peak heating (cooling) loads, and roof temperatures of residential buildings. The annual heating (cooling) loads, peak heating (cooling) loads, and exterior roof temperatures for a small compact ranch house are computed using the Thermal Analysis Research Program (TARP). The thermal performance requirements for the thermal envelope of the residence are based on prescriptive criteria given in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) Standard 90.2-1993. The residential models, with minor modifications in the thermal envelope for different locations, are subjected to hourly weather data for one year compiled in the Weather Year for Energy Calculations (WYEC) for in the following locations: Birmingham, Alabama; Bismarck, North Dakota; Miami, Florida; Phoenix, Arizona; Portland, Maine; and, Washington, D.C.

Building loads have been determined for a full factorial experimental design that varies the following parameters of the residential model: solar reflectance of the roof, ceiling thermal resistance, attic ventilation, and attic mass framing area. Attic mass framing area is defined as the exposed surface area of framing within the attic. The values for solar reflectance for the roof are varied from 0.1 to 0.8; ceiling thermal resistance, from “uninsulated” to $R-8.6 \text{ m}^2\cdot\text{K/W}$ ($R-49 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F/Btu}$); attic ventilation, from 0.5 h^{-1} to 9.2 h^{-1} ; and, attic mass framing area from 31.0 m^2 to 46.5 m^2 . The computed results for annual heating (cooling) loads and peak heating (cooling) loads are illustrated graphically, both globally for all cities and locally for each geographic location. The effect of each parameter is ranked (highest to lowest) for effect on annual heating and cooling loads, and peak heating and cooling loads. A parametric study plots the building loads as a function of roof solar reflectance for different levels of ceiling thermal resistances and for each geographic location.

An analysis of building loads is presented for the building model conditioned under a transient solar profile and steady ambient conditions of either $-1.1 \text{ }^\circ\text{C}$ ($30 \text{ }^\circ\text{F}$) for heating, or $26.7 \text{ }^\circ\text{C}$ ($80 \text{ }^\circ\text{F}$) for cooling. The time of year is specifically selected to provide equal hours of night and day. The site location for the model, in this case, is arbitrarily selected. Values for roof solar reflectance are varied from 0.1 to 0.8 and the ceiling thermal resistance, from “uninsulated” to $R-6.7 \text{ m}^2\cdot\text{K/W}$ ($R-38 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F/Btu}$). Hourly predicted profiles are presented for the cooling load, attic air temperature, and outside roof heat flux. The results are in agreement with the annual loads computed for hourly weather data and indicate that radiative cooling of the structure at night is significant. The presence of thermal insulation in the ceiling reduced the effect.

Additional simulations are conducted for each location to determine the predicted exterior roof temperatures of the residential model for one year of weather data. For these simulations only the roof solar reflectance is varied. The other building parameters are fixed at “base” levels as specified by ASHRAE Standard 90.2-1993. The effect of roof solar reflectance is presented graphically using a box plot to summarize statistically all 8760 exterior roof temperatures. The results indicate a significant reduction in peak roof temperatures is possible for high levels of solar reflectance.

Additional plots for the daily roof temperature profiles for a typical summer day and average monthly temperatures for one year are also presented.

Included in this report is a simple economic analysis that examines cost savings for each geographic location. The estimated annual energy costs for electric and gas heating are plotted versus roof solar reflectance for different levels of ceiling thermal resistance. For a residence without attic insulation in a hot climate, substantial savings are available by making the roof more reflective. At higher levels of ceiling thermal resistance, the savings are less.

Keywords

ASHRAE; absorptance; attic; building technology; cooling; energy; experimental design; heating; heat transmission; loads; model; radiation; reflectance; residence; roof; solar; TARP; temperature; thermal resistance; ventilation; WYEC

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INTRODUCTION

A reflective coating, when applied to the exterior of a building, is designed to reflect incident shortwave solar radiation, thereby reducing the cooling requirements for a conditioned space. The practice is not new. Buildings in hot climates have long utilized light color construction (i.e., whitewashing) to minimize solar heat gains (Givoni 1969). In recent years, this design philosophy has received renewed attention in the United States, particularly in southern states with hot climates. Recent field studies by Parker et al. (1994) have demonstrated that reflective coatings for residential roofs can significantly reduce the cooling loads for buildings located in hot climates. Further, using reflective coating materials in entire communities has been proposed as a means for mitigating the temperature effect of urban heat islands (Akbari et al. 1995).

These studies indicate that significant reductions in the energy required for space cooling are possible, particularly in hot climates. The reduction in space cooling has generally been found to be more pronounced for residential buildings that are not very well insulated (i.e., low ceiling thermal resistance). In order to gain a better understanding of the subject, the National Institute of Standards and Technology (NIST) conducted an analytical study of a small, compact residential building using the Thermal Analysis Research Program (Walton 1983). The objective of the study was to address the following issues.

- How do the building parameters associated with the attic - roof solar reflectance, ceiling thermal resistance, ventilation, or framing mass area - affect the heating and cooling loads of the building in different climates? Which parameter is the most important?
- What is the impact of reflective roofs for thermally efficient construction, in particular, for newer residential construction with high ceiling thermal resistances?
- Does the presence of a reflective roof cause an undesired increase in the heating load during the winter heating season? If so, what is the net effect on annual loads?
- Finally, how do solar reflective roofs affect overall performance of a residence?

With regards to the last question, this report addresses four performance measures: annual heating (cooling) loads, peak heating (cooling) loads, exterior roof temperatures, and economic cost analysis. Depending on the reader - consumer, energy producer, or roof material manufacturer - these items may be useful for assessing the impact of a solar reflective roof.

The geographic locations selected for this study cover a wide range of climates in the contiguous United States; they are: Birmingham, Alabama; Bismarck, North Dakota; Miami, Florida; Phoenix, Arizona; Portland, Maine; and, Washington, D.C. The associated climatic data for heating and cooling ranged from 152 heating degree days, base 18 °C (HDD18 or 273 HDD65) to 5044 HDD18 (9080 HDD65), and from 613 cooling degree hours base 23 °C (CDH23 or 1104 CDH74) to 30224 CDH23 (54404 CDH74), respectively. Models of the residential building were prepared

based on architectural guidelines of a small one-story "ranch style" house and the thermal performance requirements for the thermal envelope given in ASHRAE Standard 90.2-1993. The residential buildings were exposed to one year of hourly weather data compiled in the Weather Year for Energy Calculations (WYEC) by ASHRAE (Crow 1981).

For the analysis of building loads, an experimental design was utilized that collectively treated the effect of roof solar reflectance, geographic location, ceiling thermal resistance, attic ventilation, and attic mass framing area. In these simulations, the prime factor of interest was solar reflectance. The other factors were treated statistically as "nuisance" factors. To examine the effect of each factor at each level required 2700 separate computer simulations. Annual heating (cooling) loads and hourly peak heating (cooling) loads were extracted from each TARP output file and subsequently analyzed graphically using a statistical plotting program. An extended analysis of building loads was conducted for the model subjected to constant ambient air temperatures.

Additional computer simulations were executed to examine the effect of the roof solar reflectance on the exterior roof temperatures. In these simulations, the other parameters - ceiling thermal resistance, attic ventilation, and attic mass framing area - were fixed at "base" levels. For each geographic location, the simulations predicted hourly exterior roof temperatures for one year and were subsequently graphed as a function of roof solar reflectance. Additional plots for the daily roof temperature profiles for a typical summer day and average monthly temperatures for one year were also prepared.

Using the predicted building loads above, a simple economic cost analysis was prepared to examine at different levels of ceiling thermal insulation the benefits of increasing roof solar reflectance. Local residential utility rates for summer 1994 and winter 1994-1995 were obtained from the National Association of Regulatory Utility Commissioners and energy costs were computed by assuming local residential performance efficiencies for electric and gas heating equipment. Additional TARP simulations were conducted to determine the latent cooling load for each geographic location. The estimated annual energy cost was graphed versus roof solar reflectance for different levels of ceiling thermal resistance and for each geographic location.

This report presents an overview of the computer program TARP, geographic locations, descriptions of the residential model (including thermal performance criteria), experimental design, results and analysis of the computer simulations. Whenever possible, data from the computer results have been prepared in a graphical format for interpretation by the reader. These plots include predicted annual heating (cooling) loads, peak heating (cooling) loads, exterior roof temperatures, and a simple economic analysis of energy costs associated with the annual building load requirements. Samples of the TARP computer input files used in the analysis are provided in the appendices.

THERMAL ANALYSIS RESEARCH PROGRAM

The Thermal Analysis Research Program (TARP) is a computer program capable of computing hour-by-hour temperatures, space heating, and cooling loads for an arbitrary building subjected to dynamic internal loads and external boundary conditions. TARP uses detailed heat balance techniques and an iterative procedure to determine heating and cooling requirements for a conditioned space. Multiple rooms are connected with the appropriate geometric data and coupled thermally with the proper heat balances on the surfaces between the respective rooms and air movements between rooms. TARP can be used to evaluate heating and cooling requirements for a single "design day" or one year of weather data. Further details on the computer algorithms are available in the TARP Reference Manual (Walton 1983).

The TARP program was written in Fortran 77 and compiled into three separate executable programs: 1) an environment file processor (EFP); 2) a building description processor (BDP); and, 3) a thermal simulation processor (TSP). The environment file processor prepares the input weather and site data. The building description processor prepares the input building data (geometries, thermal envelope specifications, zone conditions, etc.) for the simulation. The input data is subsequently processed by the thermal performance simulation processor which computes the building loads and provides report values of the results at time intervals specified by the user. The current release of TARP is portable and has been developed for execution on a personal computer (PC) in the DOS environment (i.e., text-in, text-out format). A single run of all three programs on a PC with a 486 DX CPU operating at 66 MHZ takes about two minutes.

Establishing confidence in the results of a computer simulation program is a difficult task. In general, the program can be checked against other programs, analytical test results, or, ideally, empirically data derived from field test results. TARP simulation results have been compared to empirical data collected from 6 test buildings located near NIST in Gaithersburg, Maryland (Walton and Cavanaugh 1985, Burch et al. 1986). Each test building contained a single room approximately 6.1 m by 6.1 m with a slab-on-grade foundation and pitched roof construction. The buildings had the same floor plan and orientation, but differed in exterior wall constructions. Table 1 compares predicted and measured loads for winter, spring (intermediate), and summer seasons for insulated and uninsulated exterior wall constructions. A negative value indicated that the average predicted load was less than the averaged measured load. In general, the differences for the insulated wood frame building were better than ± 21 %; for the uninsulated wall building, better than ± 9 %.

Table 1
Comparison of Average Measured and Predicted Loads
Source: Walton and Cavanaugh 1985

Case	Winter	Spring	Summer
1. Insulated Wood Frame	-2.7 %	-20.8 %	+15.6 %
2. Uninsulated Wood Frame	+6.0 %	-8.2 %	+7.8 %

WEATHER AND SITE DATA

Weather Data

The selection of geographic locations was based, in part, on the availability of local weather data for specific locations in the contiguous United States. For convenience, weather data were taken from the sets of hourly data compiled in the Weather Year for Energy Calculations (WYEC) tapes developed for ASHRAE (Crow 1981). These hourly values of data represent long-term means for temperature and solar radiation data for a geographic location (i.e., local airport data). Each tape includes 8760 sequential values of weather data such as dry-bulb and wet-bulb air temperatures, wind direction and speed, barometric pressure, and solar radiation. The data represents collectively a "typical" year of weather in the location. Presently, WYEC data has been developed for 46 locations in the United States and five in Canada.

Selection of Cities

The 46 metropolitan locations having WYEC data for the contiguous United States were ranked by the annual heating degree days or cooling degree hours using the climatic data provided in ASHRAE Standard 90.2-1993 (ASHRAE 1993), Figures 1 or 2, respectively. The purpose of ranking was to determine the range of climatic conditions for the experimental design. For heating and cooling, three cities (shown in bold) were selected as the upper value, lower value, and midpoint value. In Figure 1, the cities selected were (lowest to highest) Miami, Florida; Washington, D.C.; and, Bismarck, North Dakota. In Figure 2, the cities were (highest to lowest) Phoenix, Arizona, Birmingham, Alabama, and Portland, Maine. Hereafter, in this report, the metropolitan locations are ranked in order by heating, that is Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck. The geographic location of each city is shown in Figure 3.

Environment File Input

The site and weather data for the TARP environment file processor (EFP) were geographic location data (i.e., latitude, longitude, etc.) for computing solar position, ground temperature, and weather tape parameters (for WYEC files). A separate computer file was prepared for each geographic location. (A sample environmental input file for Miami is provided in Appendix A.) Geographic data for the cities were taken from the ASHRAE Handbook of Fundamentals (1993). In the analysis, a constant annual ground temperature was assumed for each location (Kusuda 1981). Table 2 summarizes the average annual air temperature (ASHRAE 1993), heating degree days (ASHRAE 1993), cooling degree hours (ASHRAE 1993), and average annual ground temperature (Kusuda 1981).

WYEC CITIES - RANK ORDER BY HEATING

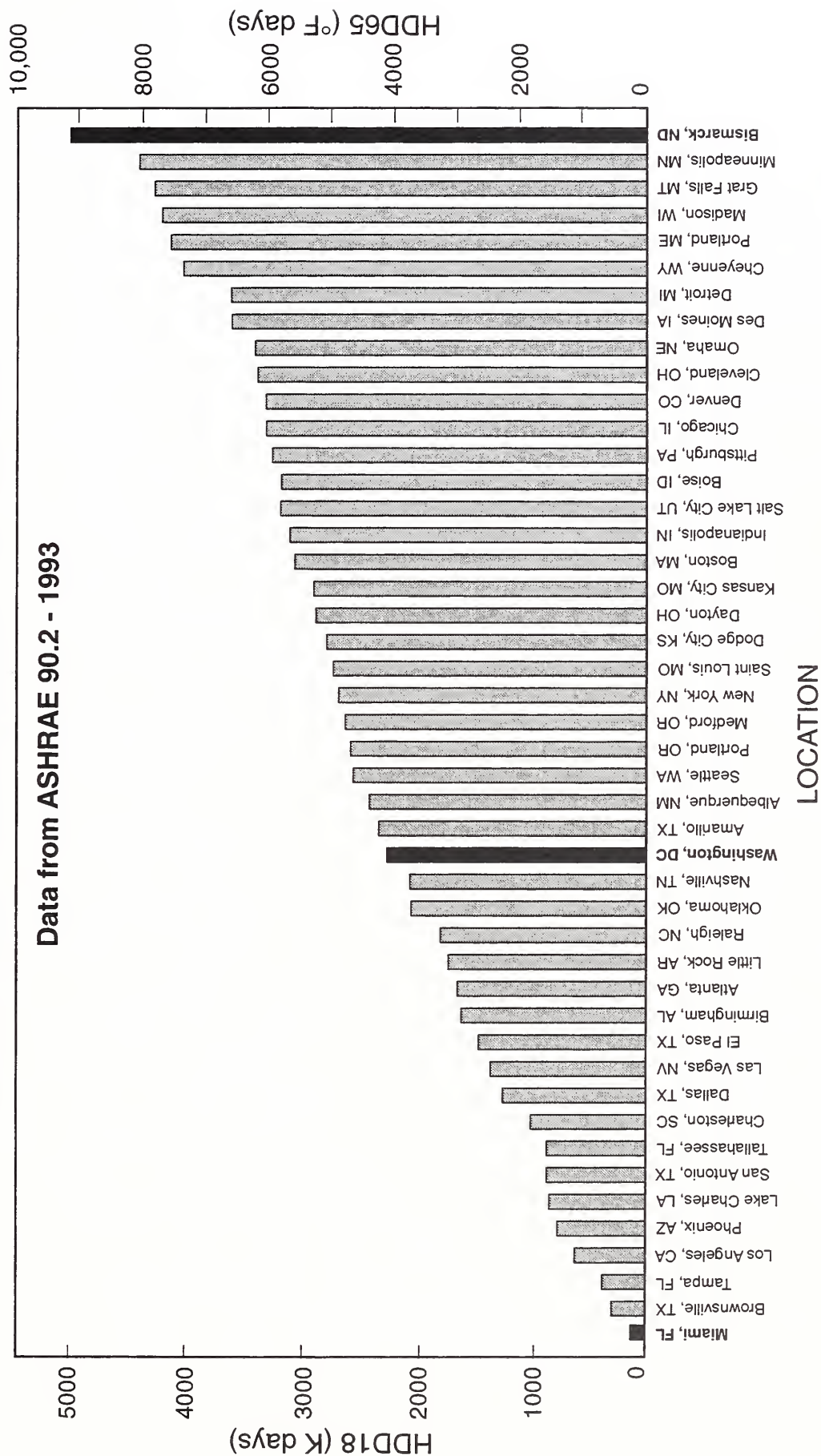


Figure 1

WYEC CITIES - RANK ORDER BY COOLING

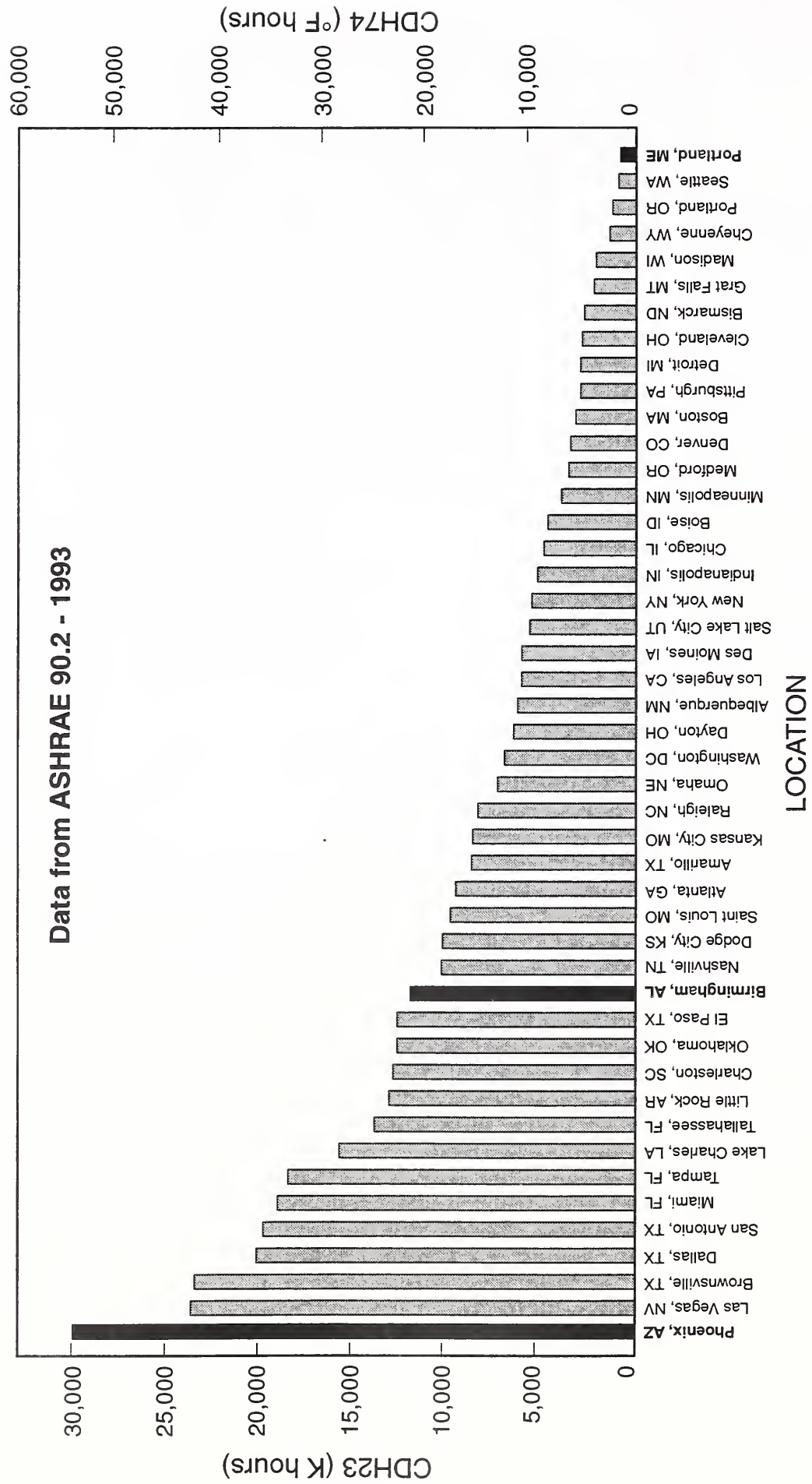


Figure 2

Location of Test Cities



Figure 3

Table 2
Temperature, Heating, and Cooling Data
Sources: ASHRAE 90.2-1993 and Kusuda (1981)

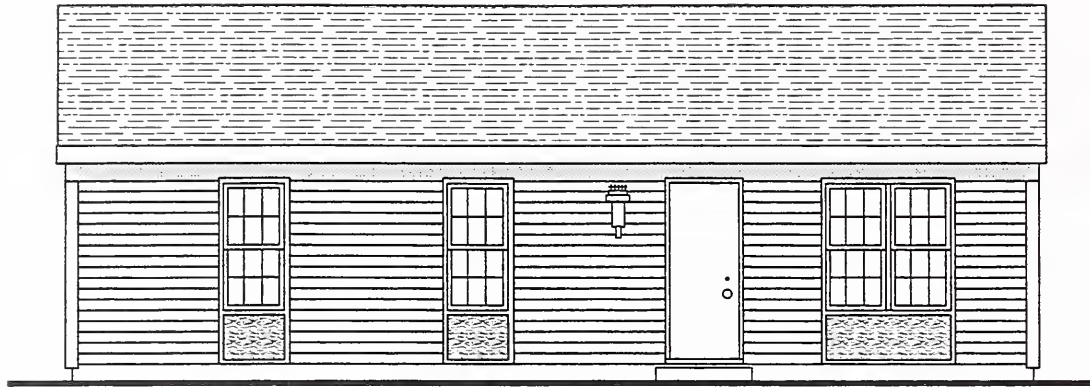
Geographic Location	Average Annual Air Temperature		Heating Degree Days		Cooling Degree Hours		Average Annual Ground Temperature	
	°C	°F	Base 18 (°C day)	Base 65 (°F day)	Base 23 (°C hour)	Base 74 (°F hour)	°C	°F
1. Miami, FL	23.9	75	152	273	19192	34545	23.9	75
2. Phoenix, AZ	21.7	71	802	1444	30224	54404	21.1	70
3. Birmingham, AL	16.7	62	1641	2953	11963	21533	17.2	63
4. Washington, DC	14.4	58	2292	4125	6883	12389	13.3	56
5. Portland, ME	7.2	45	4168	7502	613	1104	6.7	44
6. Bismarck, ND	5.0	41	5044	9080	2530	4554	5.6	42

RESIDENTIAL MODELS

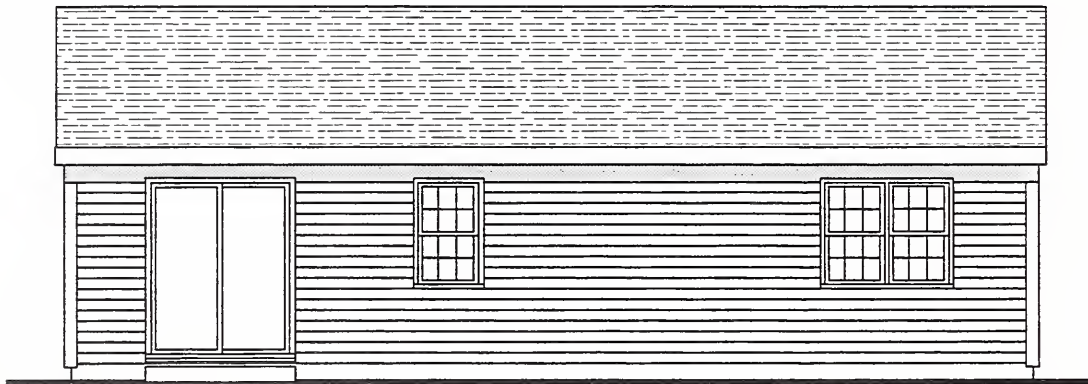
Building Geometry

The geometries for the residential building models were based on the compact, one-story, "ranch style" house specified by Hastings (1977). The elevation and plan views of the house are illustrated in Figures 4a and 4b, respectively (crawl space not shown). These architectural drawings are intended mainly as illustrations. Some of the details depicted were not included in the computer models. Figure 5 shows a cross-section view of the house illustrating a pitched roof, ventilated attic, living space, and crawl space foundation. The conditioned floor area for the house was 109 m² (1176 ft²) and the total glazing area was 11.8 m² (127 ft²), or about 11 % of the conditioned floor space, Table 3. The roof overhang extended 0.4 m (16 in.) over the front and rear elevations.

Table 3 Surface Areas of Building Envelope Components (Source: Hastings 1977)		
Component	m²	ft²
1. Crawl Space	109.3	1176
2. Crawl space wall		
a. Front	7.8	84
b. Rear	7.8	84
c. Side	5.2	56
3. Floor		
Insulation (93 %)	98.3	1058
Joists (7 %)	11.0	118
4. Frame wall		
a. Front		
Insulation (85 %)	18.2	195
Stud (25 %)	6.0	65
Window	5.1	65
Door	1.9	20
b. Rear		
Insulation (75 %)	17.7	198
Stud (25 %)	6.1	65
Window (including glass door)	6.7	72
c. Side		
Insulation (85 %)	17.7	190
Stud (15 %)	3.2	34
5. Ceiling		
Insulation (90 %)	98.3	1058
Truss cord (10 %)	11.0	118

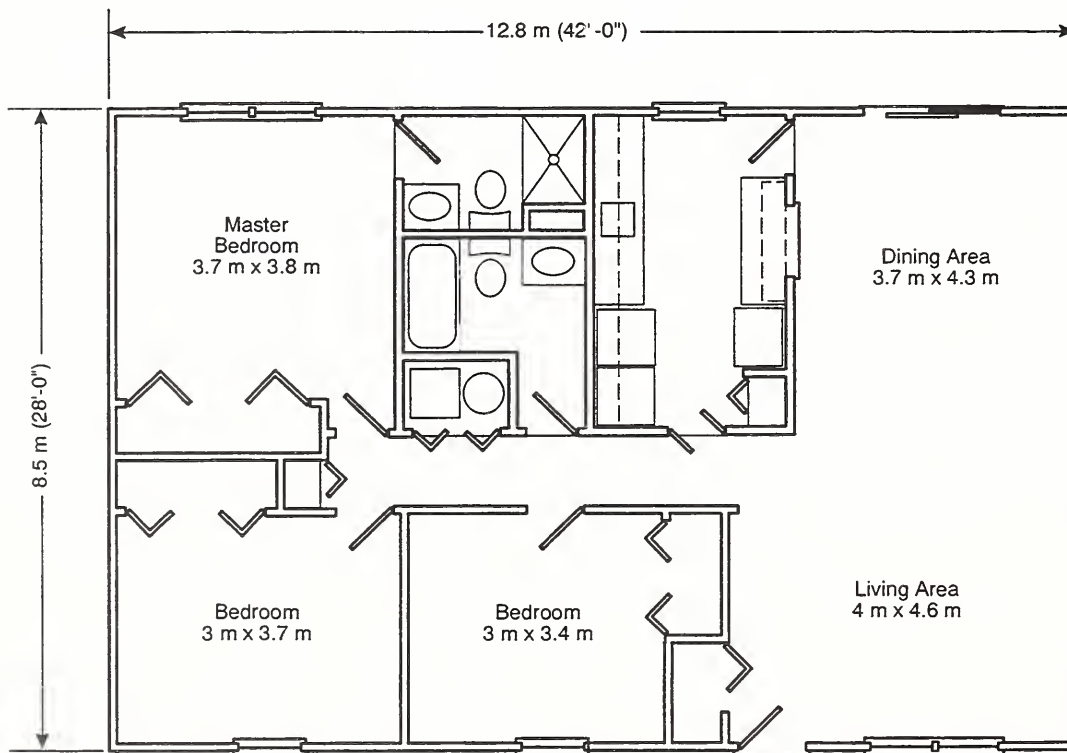


FRONT ELEVATION



REAR ELEVATION

(a)



FLOOR PLAN

(b)

Figure 4

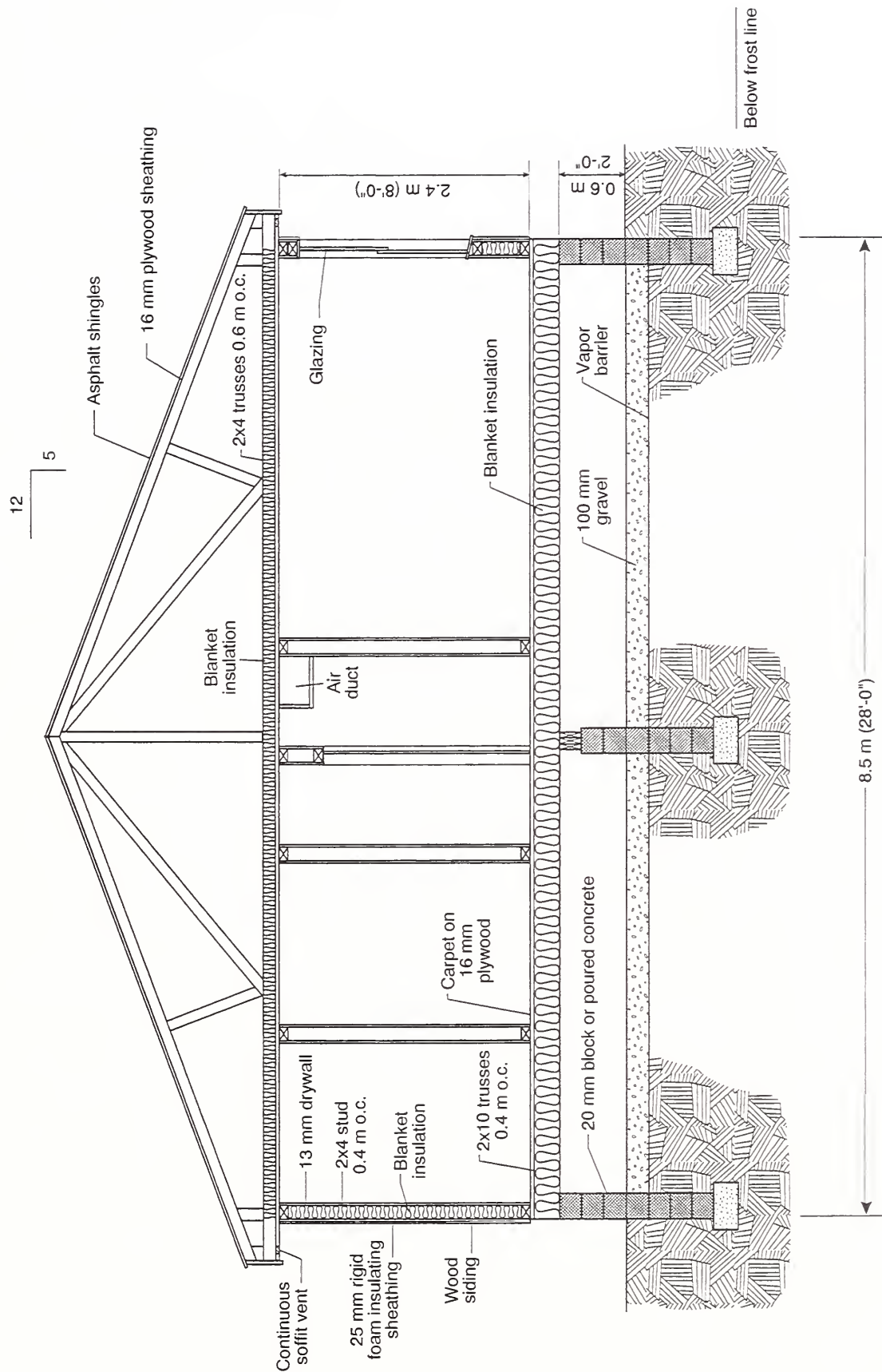


Figure 5

While in practice, the type of foundation varies with geographic location, in the analysis a crawl space foundation was modeled for all locations to simplify the comparisons of results and to minimize the effect of ground-coupling with the structure. This simplification was considered acceptable since this study focused on the interaction between the attic and living space.

Building Envelope

Using the prescriptive requirements for the building envelope given in ASHRAE Standard 90.2-1993, design values of thermal transmittance (U) were determined for each geographic location, Table 4. In this study, the duct system was assumed to be situated within the conditioned space. As noted in Table 4, values of U were generally comparable among locations, decreasing slightly for locations in colder climates. These requirements reflect a renewed interest by the authors of ASHRAE Standard 90.2-1993 in utilizing higher insulation levels for new residential construction in hot climates.

<p align="center">Table 4 Prescriptive Criteria for Building Thermal Envelope Components</p>											
Geographic Location	U-value										Glazing Shading Coef.
	Ceiling		Wall		Floor		Glazing		Door		--
	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F}$	
1. Miami, FL	0.29	0.051	0.36	0.063	0.41	0.072	7.44	1.31	2.27	0.4	0.5
2. Phoenix, AZ	0.20	0.036	0.36	0.063	0.41	0.072	4.94	0.87	2.27	0.4	0.5
3. Birmingham,	0.20	0.036	0.36	0.063	0.41	0.072	4.94	0.87	2.27	0.4	0.7
4. Washington, DC	0.20	0.036	0.36	0.063	0.41	0.072	4.94	0.87	2.27	0.4	0.7
5. Portland, ME	0.20	0.036	0.36	0.063	0.27	0.047	2.04	0.36	2.27	0.4	0.7
6. Bismarck, ND	0.20	0.036	0.36	0.063	0.27	0.047	2.04	0.36	2.27	0.4	0.7

The required levels of thermal insulation for the exterior walls, floor, and ceiling were determined using the design requirements given in Table 4. Values of thermal resistance (R-values) were determined using guidelines in the 1993 ASHRAE Handbook of Fundamentals (ASHRAE 1993). The exterior wall cavities (88 mm, 3.5 in.) of the living space were insulated with R-2.6 m²·K/W (R-15 h·ft²·°F/Btu) high-performance glass-fiber blanket insulation. The exterior sheathing consisted of 25 mm (1 in.) rigid foam board, R-0.9 m²·K/W (R-5 h·ft²·°F/Btu). The area between the floor joists (238 mm, 9.5 in.) was insulated with R-3.3 m²·K/W (R-19 h·ft²·°F/Btu) and between the ceiling joists with R-5.3 m²·K/W (R-30 h·ft²·°F/Btu) for Miami and R-6.7 m²·K/W (R-38 h·ft²·°F/Btu) elsewhere. The crawl space walls were not insulated. These levels of insulation comprise the “base case” of the model for each geographic location. Table 5 summarizes the building envelope construction details for the attic, conditioned living space, and crawl space, identified as Zone 1, 2, and 3 in the model.

Table 5
Building Envelope Constructions

Attic (vented) - Zone 1		
Pitched Roof	Attic Floor	Gable Wall
1. Asphalt shingles, 6.3 mm (¼ in.)	1. Gypsum wallboard, 13 mm (½ in.)	1. Wood siding lapped, 13 mm by 200 mm (½ in. by 8 in.)
2. Felt building membrane	2. Blanket thermal insulation	2. Fiberboard sheathing, 13 mm (½ in.)
3. Plywood sheathing, 16 mm (⅝ in.)	3. Wood floor joist, 38 mm by 88 mm (2 × 4, 24 in. on center)	3. Wood stud (neglected in model)
4. Wood ceiling rafter, 38 mm by 88 mm (2 × 4, 24 in. on center)		
Living Space - Zone 2		
Ceiling	Floor	Wall
1. Wood ceiling joist, 38 mm by 88 mm (2 × 4, 24 in. on center)	1. Wood floor joist, 38 mm by 238 mm (2 × 10, 16 in. on center)	1. Wood siding lapped, 13 mm by 200 mm (½ in. by 8 in.)
2. Blanket thermal insulation	2. Plywood subfloor, 16 mm (⅝ in.)	2. Rigid foam sheathing, 25 mm (1 in.)
3. Gypsum wallboard, 13 mm (½ in.)	3. Blanket thermal insulation	3. Wood stud, 38 mm by 88 mm (2 × 4, 16 in. on center)
	4. Carpet/rubber padding	4. Blanket thermal insulation
		5. Gypsum wallboard, 13 mm (½ in.)
Crawl Space (vented) - Zone 3		
Ceiling	Floor	Wall
1. Carpet/rubber padding	1. Gravel, 50 mm to 100 mm (2 in. to 4 in.)	1. Concrete block, 191 mm by 191 mm by 397 mm (7⅝ × 7⅝ × 15⅝ in.), 2 core
2. Plywood subfloor, 16 mm	2. Vapor barrier (neglected)	
3. Blanket thermal insulation	3. Soil (earth)	
4. Wood floor joist, 38 mm by 238 mm (2 × 10, 16 in. on center)		

Windows

To satisfy the prescriptive criteria for glazing given in Table 4, the windows were simply assumed to be single glazing units for Miami, Phoenix, Birmingham, and Washington, D.C. and double glazing, low emittance units for Portland ME and Bismarck. The shading coefficients were selected from values given in Table 4. In practice, shading coefficients of 0.7 are achieved with window treatments (i.e., shades and/or draperies), coefficients of 0.5 with special coatings in addition to the standard window treatment. The total window area of 11.8 m² (127 ft²) was slightly higher than the 11.6-m² (125-ft²) prescriptive requirement of ASHRAE Standard 90.2-1993.

Thermal Properties

The thermal properties of the construction materials were taken from the 1993 ASHRAE Handbook of Fundamentals (ASHRAE 1993), Table 6. In accordance with ASHRAE 90.2-1993, the solar radiation absorptance of all exterior surfaces, except the asphalt roof shingles, was set to a fixed value of 0.5. The thermal radiation emittance of all exterior surfaces was set to 0.9.

Table 6 Thermal Transmission Data for Building Materials Source: 1993 ASHRAE Handbook of Fundamentals								
Material	k-factor		Density		Specific Heat		R-value	
	W/m·K	Btu/h·ft·°F	kg/m ³	lb/ft ³	kJ/kg·K	Btu/lb·°F	m ² ·K/W	h·ft ² ·°F/Btu
Air space, vertical	---	---	---	---	---	---	0.16	0.91
Asphalt roof shingle	0.041	0.024	1120	70	1.26	0.30	---	---
Carpet & rubber pad	---	---	---	---	---	---	0.22	1.23
Concrete block	1.13	0.65	2180	136	0.92	0.22	---	---
Felt	---	---	---	---	---	---	0.01	0.06
Fiberboard sheathing	0.055	0.032	290	18	1.30	0.31	---	---
Glass-fiber batt	---	1	---	---	---	---	1.3 to 8.6	11 to 49
Glazing, double pane	---	---	---	---	---	---	0.35	1.98
Glazing, single pane	---	---	---	---	---	---	0.05	0.28
Gypsum wallboard	0.16	0.093	800	50	1.09	0.26	---	---
Plywood sheathing	0.12	0.067	550	34	1.21	0.29	---	---
Polystyrene foam	0.029	0.017	43	2.7	1.21	0.29	---	---
Softwood framing	0.12	0.067	610	38	1.63	0.39	---	---
Soil (earth)	1.73	1	1040	65	0.8	0.19	---	---
Gravel	10.3	6	2880	180	0.84	0.20	---	---
Wood door	---	---	---	---	---	---	0.29	1.65
Wood siding, lapped	0.09	0.051	430	27	1.17	0.28	---	---

Site and Shading

The residential models were oriented with their elongated dimension parallel to an east-west axis and the pitched roof was modeled with an attached overhang, 0.4 m (16 in.) in length. In the analysis, only shading from attached surfaces such as the overhang was considered. Shading from the surroundings, such as other buildings, trees, etc., was not considered.

Thermostat Settings

The house was modeled as three separate zones: a ventilated attic (Zone 1); a living space (Zone 2); and, a ventilated crawl space (Zone 3). The entire living space (Zone 2) was assumed to be conditioned as a single thermostatically controlled zone. The other zones were unconditioned and the air temperatures drifted in response to outdoor conditions. The temperature set points for the living space were specified in accordance with ASHRAE Standard 90.2-1993 (ASHRAE 1993). The heating thermostat setting was fixed at 20 °C (68 °F) from 6 AM to 11 PM (06:00 to 23:00) and 15.6 °C (60 °F) from 11 PM to 6 AM (23:00 to 06:00). The cooling thermostat setting was fixed at a constant value of 25.6 °C (78 °F). The conditioned space was maintained at the specified thermostat settings during the entire year. Natural ventilation, although beneficial during the cooling season, was not considered in the analysis.

Internal Loads

The living space was assumed to have a daily internal load (Q_i) of 47.7 MJ/day (or 5.0 W/m²) from lights, people, and equipment based on Equation (1) (ASHRAE 1993):

$$Q_i = Q_{sen} + Q_{lat} \quad (1)$$

where;

Q_{sen} = sensible heat gain [MJ/day]; and,

Q_{lat} = latent heat gain [MJ/day].

For a single zone, the latent heat gains was assumed to be 20 % of the sensible heat gain (ASHRAE 1993). The daily sensible heat gain was determined from Equation (2) (ASHRAE 1993):

$$Q_{sen} = 1055 \left[(floor\ area) \times 15 \frac{Btu}{day \cdot ft^2} + 20,000 \frac{Btu}{day} \right] \quad (2)$$

The daily profile for the residences was determined based on the hourly fractional multipliers given in ASHRAE Standard 90.2-1993 (see Table 8-1, ASHRAE 1993), Figure 6. For the analysis, the day schedules of the lighting, people, and equipment were adjusted to provide an hourly internal gain heat profile, Figure 6. Other non-conditioning loads, such as water heating, were not considered.

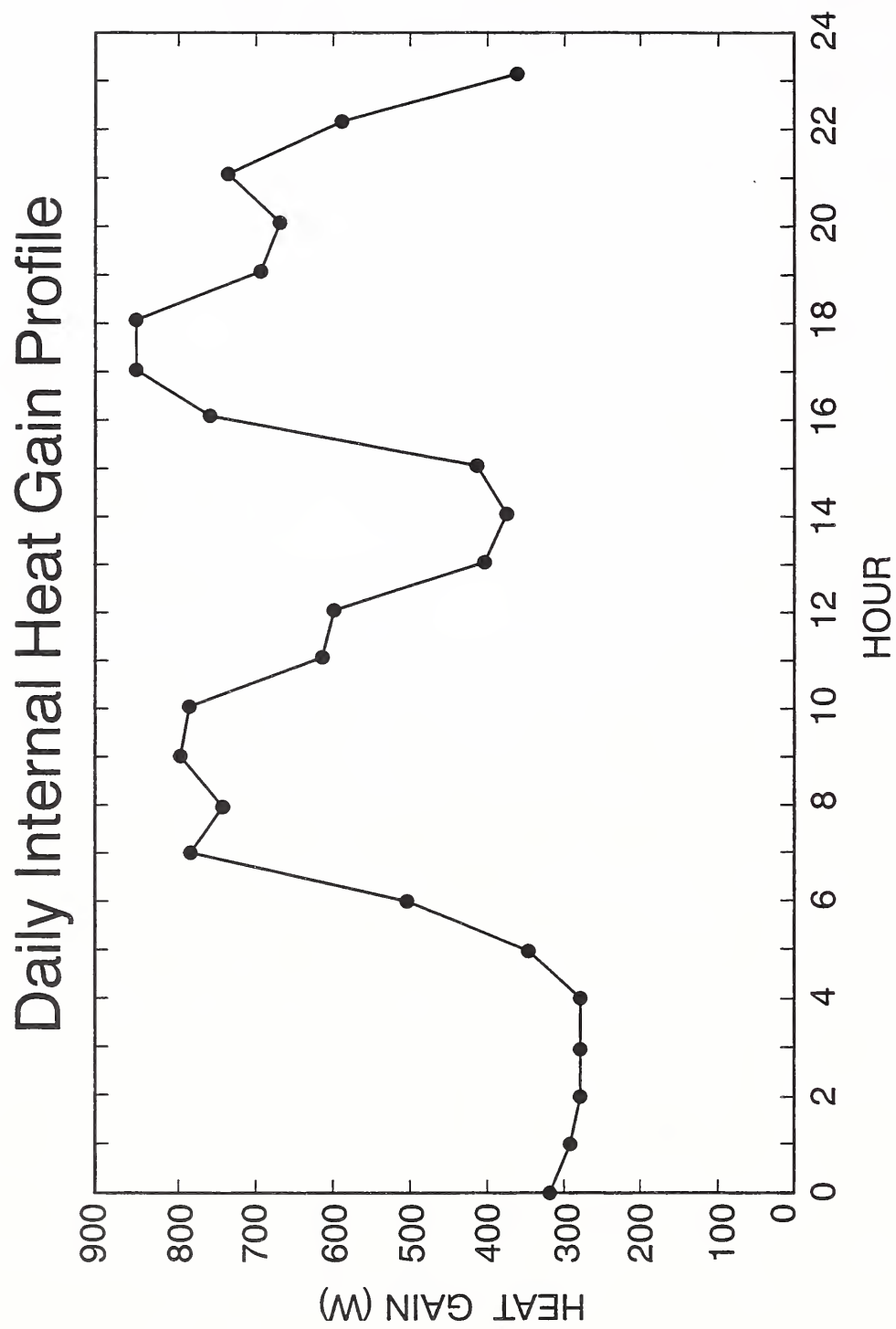


Figure 6

Building Description Input

The building description data was prepared by the TARP building description processor (BDP). An example of BDP input files (for Miami) is provided in Appendix B. The temperature and loads convergence limits for the heat balance calculations were 0.05 °C (0.09 °F) and 0.01 W (0.01 Btu/h), respectively. The radiant interchange between room surfaces was computed using the mean radiant temperature network method (Carroll 1980) and the exterior and internal heat transfer coefficients were determined using the an algorithm that included forced convection, natural convection, and radiant interchange (Walton 1983). The ventilation rate for the attic (Zone 1) was varied at constant levels according following the experimental design. Infiltration rates for the living space (Zone 2) and crawl space (Zone 3) were fixed at constant infiltration rates of 0.5 h⁻¹ (ASHRAE 90.2-1993) and 1.0 h⁻¹ (Samuelson 1994), respectively.

EXPERIMENTAL DESIGN

Test Plan

The experimental plan was a full-factorial design for the five factors shown in Table 7. The full factorial design consisted of all possible combinations of levels of the five factors, so the total number of runs is 2700 ($=6 \times 5 \times 6 \times 5 \times 3$). Obviously, for this study, the primary factor was the solar reflectance of the roof. The other factors in Table 7 were, statistically speaking, considered to be "nuisance" factors.

Table 7 Factor and Levels for Building Loads Analysis	
1	Geographic location (city) - 6 levels: 1) Miami FL, 2) Phoenix AZ, 3) Birmingham AL, 4) Washington DC, 5) Portland ME, 6) Bismarck ND
2	Roof solar reflectance (ρ) - 5 levels: 0.10, 0.30, 0.45, 0.60, 0.80
3	Ceiling thermal resistance (R-value) - 6 levels: a) none, 1.9, 3.3, 5.3, 6.7, 8.6 ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) b) none, 11, 19, 30, 38, 49 ($\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F} \cdot \text{Btu}^{-1}$)
4	Attic ventilation rate - 5 levels: 0.5, 2.3, 4.6, 6.9, 9.2 ($\text{air change} \cdot \text{h}^{-1}$)
5	Attic mass framing area - 3 levels: a) 31.0, 38.7, 46.5 (m^2) b) 333, 417, 501 (ft^2)

Factors and Levels

In Table 7, the cities were ranked from lowest to highest by heating degree days, base 18 °C (see Table 2). This order is used hereafter in all plots and test results. As described above, these geographic locations were selected to cover a wide range of climatic conditions for the contiguous United States (Figures 1 and 2).

Five levels were selected for solar reflectance. The lower and upper values of 0.10 and 0.80 were based on measured extremes of building roofing products published in the literature (Berdahl 1994, Yarbrough 1994). A value of 0.10 corresponded to a dark or black-color shingle and a value of 0.80 corresponded to a highly reflective exterior radiation coating. In actuality, these values are somewhat extreme (particularly the upper limit), therefore, several intermediate values were also

selected. Intermediate values of ρ were representative of either different color shingles (Reagan and Acklam 1979), or indicative of a “dirty or aged” reflective radiation coating (Bretz and Akbari 1994). In the TARP simulations, values for the solar absorptance (α) of the roof were computed from Equation (3).

$$\rho + \alpha = 1 \quad (3)$$

The levels for the ceiling thermal resistance (R-value) were based, in part, on criteria specified in ASHRAE 90.2 (ASHRAE 1993) and the DOE Insulation Fact Sheet (Department of Energy 1987). These publications typically recommended ceiling insulation values ranging from R-3.3 m²·K/W to R-8.6 m²·K/W (R-19 h·ft²·°F/Btu to R-49 h·ft²·°F/Btu) depending on geographic location. The minimum level of “none” was based on information compiled in Housing Characteristics 1990 (DOE 1992) which stated that, in 1990, a remarkable 19 % of single-family housing units in the United States had no ceiling insulation.

The attic ventilation rates were fixed at one of five levels for wind speeds ranging from 0.4 m/s to 8.9 m/s (1 mph to 20 mph). Table 8 summarizes wind speeds and attic ventilation rates for the five levels. The low level represented a poorly ventilated attic and the upper level a well-ventilated attic. An effective air leakage area (ELA) ratio of 300 for the floor-to-vent area was assumed. The volume of the attic was 106.4 m³. Using empirical data compiled for the Canada Mortgage and Housing Corporation (Buchan, Lawton, Parent Ltd. 1991), a relation for ventilation rate (\dot{V}_a) as a function of the wind speed was developed by Burch (1996):

$$\dot{V}_a = ELA (b v^2)^{1/2} \quad (4)$$

where;

b = empirically derived regression coefficient (m²); and,
v = wind speed (m/s).

Table 8 Attic Ventilation Rates for Different Wind Speeds					
Level	Wind Speed		Attic Ventilation Rate		
	m/s	mph	m ³ /s	cfm	air change/h
1	0.4	1	0.015	31	0.5
2	2.2	5	0.074	157	2.3
3	4.5	10	0.148	315	4.6
4	6.7	15	0.223	472	6.9
5	8.9	20	0.297	629	9.2

In the analysis, the mass framing area of the attic trusses was assumed to respond slowly to temperature changes and was modeled as an internal surface. The construction for the attic mass was modeled as wood and the surface area was set to one of three levels (Table 7). The mid-value for surface area was determined for 22 trusses, 0.6 m (24 in.) on center. Upper and lower values were computed using $\pm 20\%$ of the mid-value.

Simulation Runs for Building Loads

As before, the term full factorial means all possible combinations of settings for the five factors given in Table 7. There were 2700 ($=6 \times 5 \times 6 \times 5 \times 3$) combinations and hence 2700 simulation runs. The advantage of such a design is that all factors may be treated equivalently in the analysis, thus yielding conclusions that were truly global in nature, i.e., more robust. The disadvantage is that analysis of optimal settings for one factor, for example solar roof reflectance, would require analysis of subsets of data. Table 9 illustrates the development of the full factorial design undertaken for the study of building loads.

Table 9 Development of Full Factorial Design					
Run	Factor and Level				
	x_1	x_2	x_3	x_4	x_5
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	1	3
4	1	1	1	2	1
5	1	1	1	2	2
6	1	1	1	2	3
7	1	1	1	3	1
⋮	⋮	⋮	⋮	⋮	⋮
2698	6	5	6	5	1
2699	6	5	6	5	2
2700	6	5	6	5	3

As observed in Table 9, the full-factorial design was developed systematically by varying each factor at all possible settings; in this case, starting with x_5 (attic mass framing area) and proceeding to x_4 , x_3 , x_2 , and x_1 . Therefore, for each geographic location, 450 ($5 \times 6 \times 5 \times 3$) separate simulation runs were conducted. For example, run #4 (11121) is for Miami FL with the following levels for the other factors: a solar roof reflectance of 0.1; ceiling thermal resistance of "none"; attic ventilation rate of 2.3 h^{-1} ; and, attic mass framing area of 31.0 m^2 . The last run for Miami is #450 (15653) which

would have a solar roof reflectance of 0.8; ceiling thermal resistance of $R-8.6 \text{ m}^2\cdot\text{K}/\text{W}$; attic ventilation rate of 9.2 h^{-1} ; and, attic mass framing area of 46.5 m^2 . Completing this approach, run #2700 (65653) is for Bismarck ND with a solar roof reflectance of 0.8; ceiling thermal resistance of $R-8.6 \text{ m}^2\cdot\text{K}/\text{W}$ attic ventilation rate of 9.2 h^{-1} ; and, attic mass framing area of 46.5 m^2 .

The 2700 input building description files for TARP were prepared as follows. Initially, a single file for Miami, Florida was prepared (see Appendix B for sample). The building description files for the other cities were prepared from the Miami input file by essentially modifying the prescriptive criteria of the building envelope in accordance with values given in Table 4. A BASIC program was subsequently used to generate the 2700 separate building description files needed for the analysis. Using a DOS batch file, all 2700 simulations were executed in 31 hours on a personal computer with a 486 DX CPU operating at 66 megahertz.

The output file of each TARP simulation run provided the following heating and cooling requirements for the conditioned living space (Zone 2): 1) the predicted annual heating and sensible cooling loads in MJ (or kBtu) (i.e., cumulative); and, 2) the predicted hourly peak heating and sensible cooling loads in kW. Hereafter, unless described otherwise, the term cooling load is taken to mean *sensible* cooling load. Latent cooling loads are treated later for the economic analysis. Note that only Zone 2 is conditioned in the model. Therefore, the heating and cooling requirements for Zone 2 (i.e., living space) are the same requirements for the building itself. It is also important to note that the results obtained for hourly peak loads are not to be confused with design loads that are calculated under specific design conditions. Using a (post-processor) BASIC program, the 2700 values of predicted annual heating and cooling loads and hourly peak heating and cooling loads were compiled into a single data file and subsequently analyzed with the NIST statistical plotting package, Dataplot (Filliben 1977).

BUILDING LOADS

This section presents the building load results for the 2700 TARP simulation runs plotted versus the input factors. Annual heating (cooling) loads and peak heating (cooling) loads are first ranked on a global basis, that is, collectively for all five factors. Next, the results are ranked locally for each geographic location comparing only three factors - roof solar reflectance, ceiling thermal resistance, and attic ventilation. Finally, a subset of the annual heating (cooling) loads and peak heating (cooling) loads is plotted as a function of roof solar reflectance for different levels of ceiling thermal resistance.

Global Ranking of the Factors

The five factors - city, roof solar reflectance, ceiling thermal resistance (R-value in the plots), attic ventilation, and attic mass framing area - were ranked (largest effect to smallest) using the design of experiment (dex) mean plot. This plot determines the mean value of the response variable for each level of each factor. The analysis is valid because the experimental design is balanced (see Experimental Design). That is, any particular value of the response variables has an equal number of runs for each independent factor. The advantage of this analysis is that general conclusions can be deduced quickly for the best settings (levels) of each factor. The disadvantage is that each point contains variations (or contamination) due to the other four factors. Therefore, optimal local settings of each factor require analysis of a subset of data. Figures 7 and 8 illustrate the dex-mean plot for annual heating (cooling) loads and peak heating (cooling) loads, respectively.

In Figure 7a, mean values for annual heating load (in megajoules [MJ]) are plotted on the y-axis versus the five input factors on the x-axis. For each factor on the x-axis, the data are plotted in the order shown in Table 7 from left to right. For example, the left point for city represents the average heating load of 450 simulation runs for Miami and the right point represents the average of 450 simulation runs for Bismarck. The plot shows a monotonic trend for each factor. The global ranking (i.e., largest effect to smallest) for each factor is as follows: city; ceiling R-value; roof solar reflectance or attic ventilation; and, mass framing area which was inconsequential. For all locations, the largest reduction in annual heating load was due to ceiling R-value. Moreover, the lowest annual heating load was at the highest level of ceiling insulation. Not surprisingly, the greatest reduction was due to adding the first level of ceiling insulation to an uninsulated attic. Thereafter, the reductions diminished for higher levels of ceiling R-value. Higher levels of solar reflectance and attic ventilation increased the annual heating load (sometimes referred to as heating penalty).

Figure 7b plots mean values for annual cooling load on the y-axis versus the five input factors on the x-axis. In this case, since the cities are ranked by heating degree days, the trend for city is not monotonic. The annual cooling loads required for Phoenix (level 2) and Portland ME (level 5) were the highest and lowest, respectively. The global ranking for each factor from highest to lowest effect is city, ceiling R-value, roof solar reflectance, ventilation, and mass framing area which was again inconsequential. As observed above in Figure 7a, a large reduction in annual cooling resulted by adding thermal insulation to an uninsulated attic with diminishing effects thereafter. However,

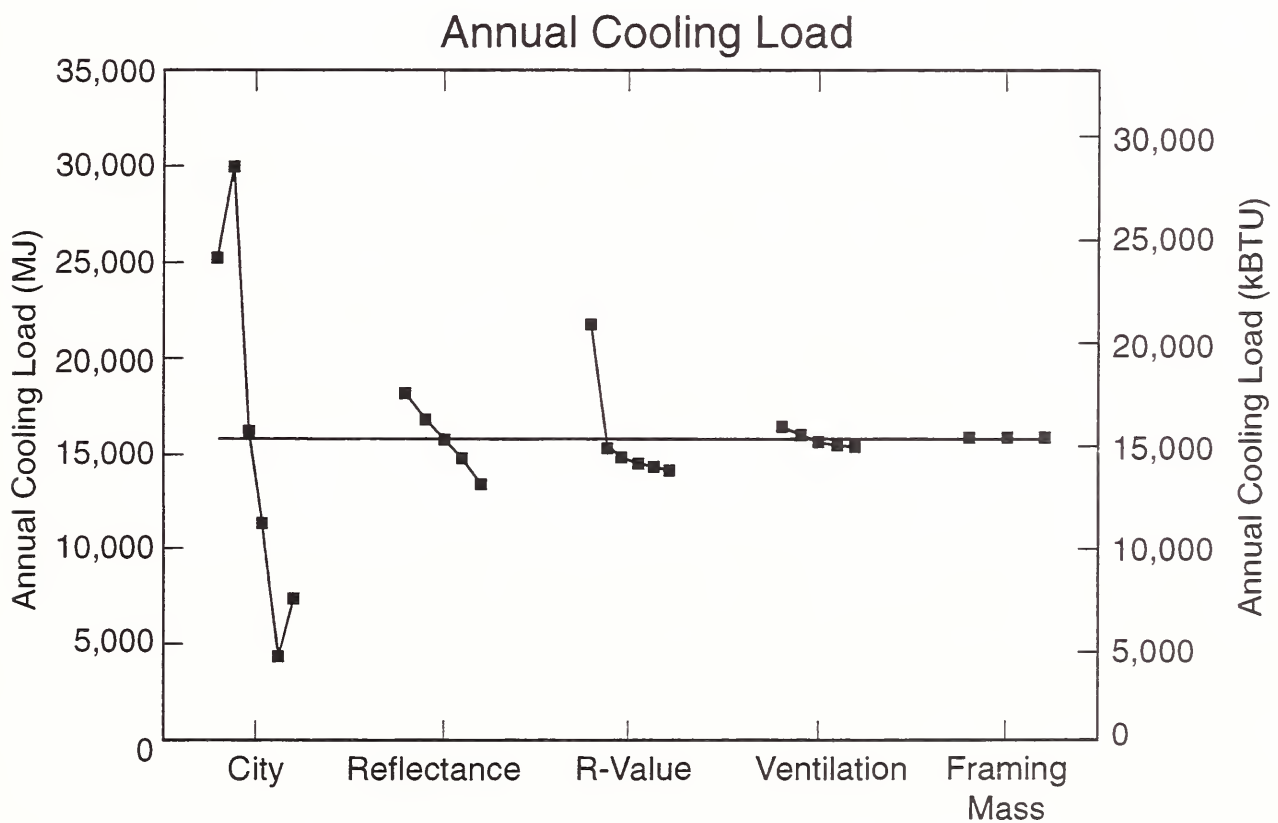
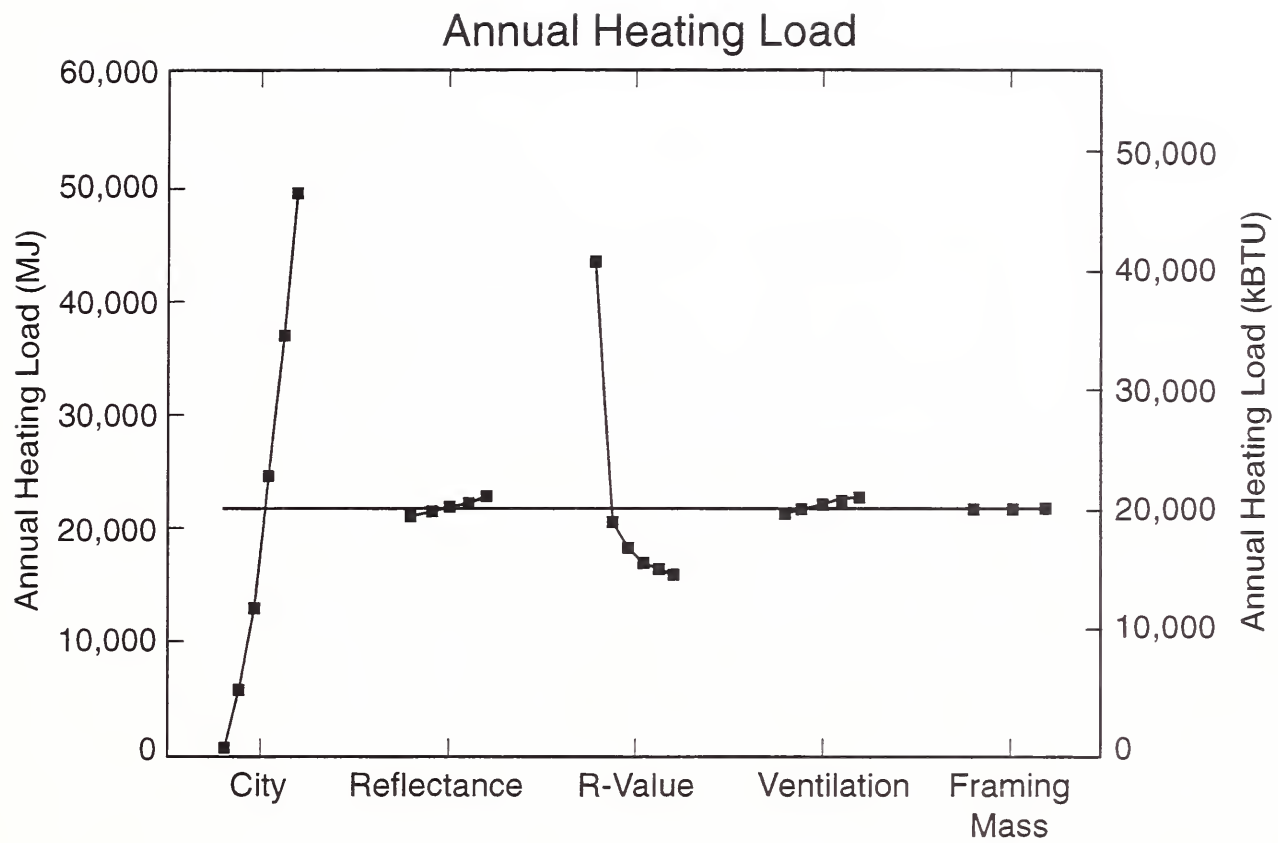


Figure 7

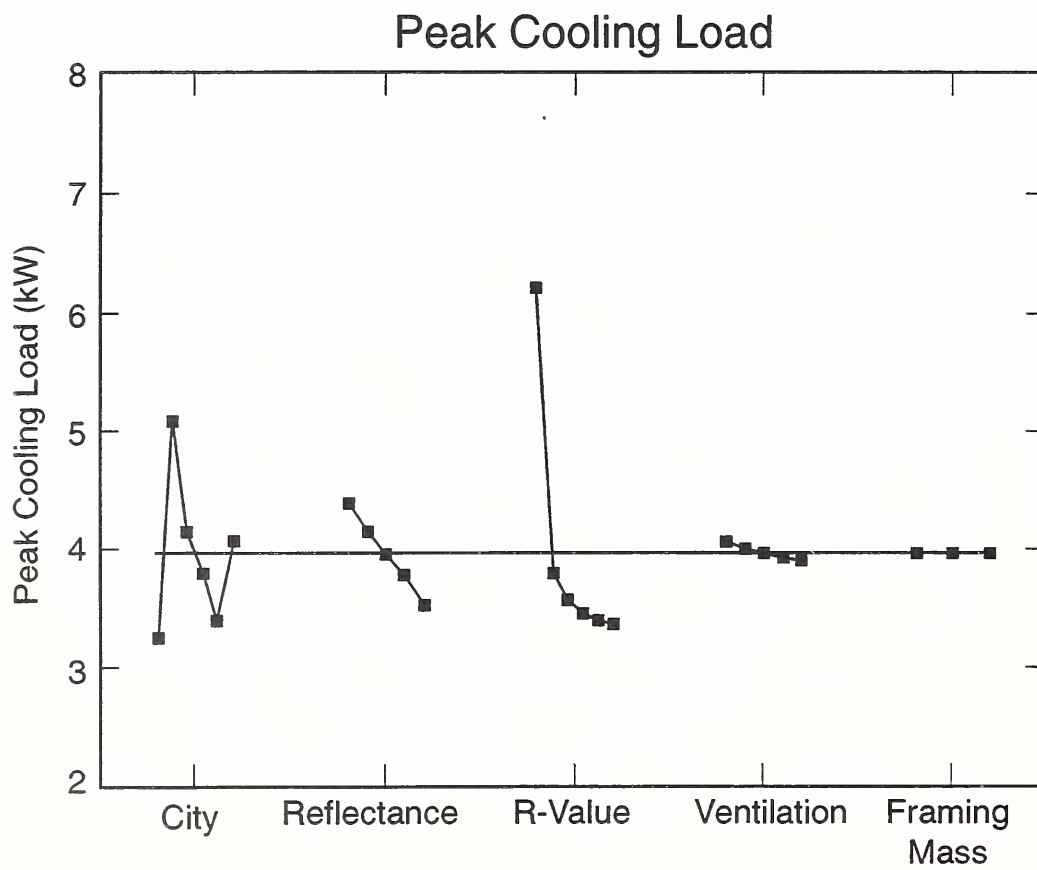
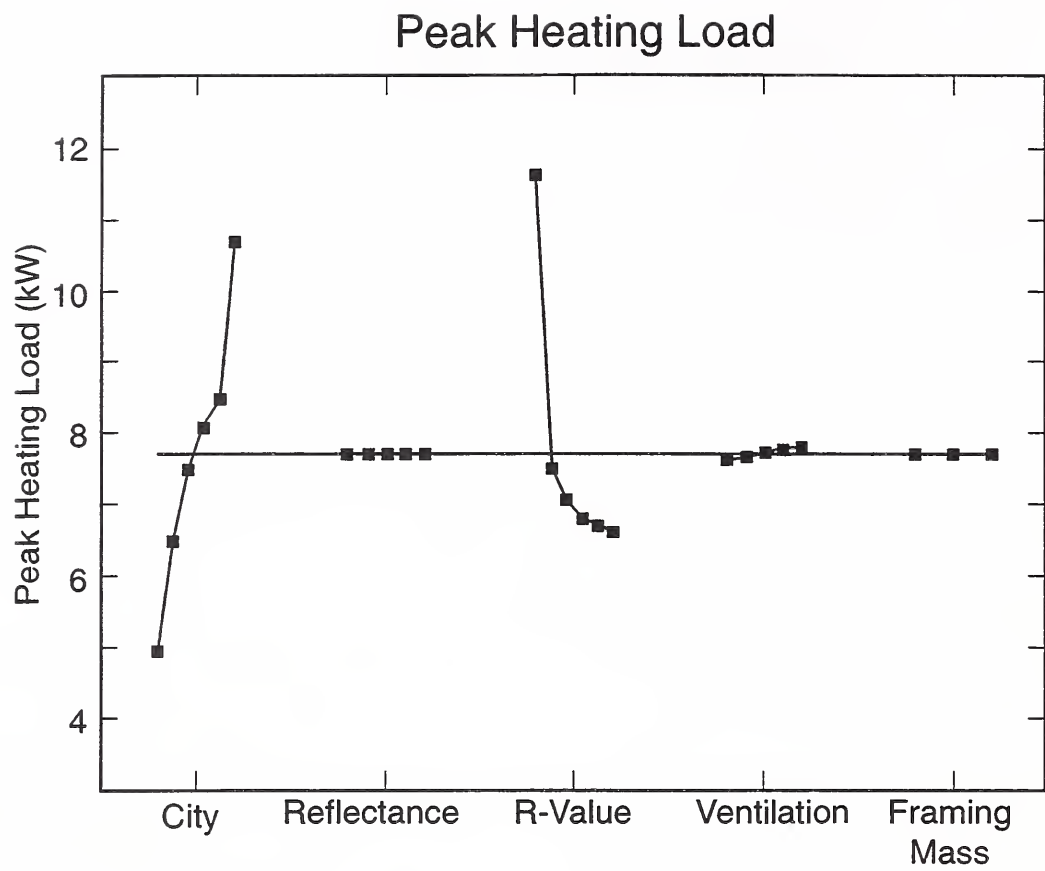


Figure 8

contrary to the annual heating results, the roof solar reflectance significantly reduced the annual cooling load. In fact, on average, the lowest annual cooling load for each and all locations and for each and all R-values occurred at the highest level of solar reflectance (Figure 7b). The reduction in annual cooling appears to be linearly related to roof solar reflectance. In general, higher levels of attic ventilation also decreased the annual cooling load, although to a lesser extent.

Figure 8a plots mean values for the hourly peak heating load (in kilowatts [kW]) on the y-axis versus the input factors on the x-axis. The results are similar to annual heating (Figure 7a). The global ranking for each factor is city; ceiling R-value, and, ventilation. The effects of roof solar reflectance and attic framing mass were both inconsequential (Figure 8a). Typically, peak heating for a residence occurs at night and, therefore, changes in roof solar reflectance would have no effect.

Figure 8b plots mean values for hourly peak cooling load on the y-axis versus the input factors on the x-axis. Here, the results are similar to annual cooling (Figure 7b), except for two findings. Ceiling R-value caused the greatest effect and the lowest peak cooling load was for Miami. Like annual cooling, the hourly peak cooling load was linearly related to the roof solar reflectance.

The global rank for the factors in Figures 7 and 8 are summarized in Table 10. In general, the geographic location of the city had the greatest effect, that is, the greatest overall change on building loads, in all cases except for hourly peak cooling. The next factor was ceiling R-value which was always beneficial, meaning higher levels of the ceiling R-value decreased both heating and cooling loads. In all cases, increasing the attic insulation from “none,” (uninsulated case) to the first level of $R-1.9 \text{ m}^2\cdot\text{K/W}$ ($R-11 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F/Btu}$) resulted in the greatest load reduction. Thereafter, the incremental benefits diminished for each subsequent level of attic insulation. The roof solar reflectance was beneficial for cooling loads (both annual and hourly peak), detrimental for annual heating, and unimportant for hourly peak heating. The beneficial effect was linearly related to the roof solar reflectance. Likewise, attic ventilation was beneficial for cooling, although to a lesser extent, and detrimental for heating. The effect of the attic mass was inconsequential for all cases and was neglected in further analysis. Recall that one of the advantages of this analysis is that general conclusions can be deduced quickly for the best settings (levels) of each factor. Unfortunately, in this case, the effect of geographic location overwhelmed the other factors and therefore was removed from subsequent analyses by evaluating the other building factors on a local level.

Table 10
Global Ranking of Factors (1 = greatest effect; 5 = least effect)

Building Load	City	ρ - Roof	Ceiling R-value	Attic Ventilation	Attic Mass
1. Annual Heating	1	3	2	3	5
2. Annual Cooling	1	3	2	4	5
3. Hourly Peak Heating	1	5	2	3	5
4. Hourly Peak Cooling	2	3	1	4	5

Ranking the Factors by City

At the global level described above, the factors of interest were ranked in order of effect for annual heating (cooling), and peak heating (cooling). As noted in Table 10, geographic location was the primary factor and, in fact, overwhelmed the effect of the other factors. Ranking the factors by city allows further insight in determining the optimum levels of factors at each geographic location. Further, a local analysis allows us to verify (and strengthen) that the above global conclusions were in fact valid for all geographic locations. In order to rank the factors by city, the dex-mean plot was applied locally; that is, on a case-by-case basis to each individual city for three factors - solar reflectance, ceiling R-value, and attic ventilation rate.

Figures 9, 10, 11, and 12 illustrate the application of the dex-mean plot for the annual heating load, annual cooling load, peak heating load, and peak cooling load, respectively. Each figure contains the same sequence of six plots for the cities: Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck. The factors of interest - solar reflectance, ceiling R-value, and attic ventilation rate - are plotted on the x-axis. Again, the levels for each factor are shown from left to right following the order in Table 7.

Examination of the data in Figures 9 to 12 reveals that the trends for each city were, for the most part, very similar to the global results presented in Figures 7 and 8. In Figure 9, the trends in the data for each factor at each geographic location changed monotonically and were in agreement with the global data in Figure 7a. At all locations, higher levels in ceiling insulation achieved the greatest reduction in annual heating. Moreover, the lowest annual heating load for each city was obtained with the highest level of attic thermal insulation. Again, the greatest reduction in annual heating load was observed by adding insulation to an uninsulated attic. Further reductions due to ceiling thermal resistance were incrementally smaller for each level of thermal resistance. Increased levels of solar reflectance and attic ventilation rates resulted in small but undesired increases in the required annual heating load, as noted previously in Figure 7a.

In Figure 10, the trends in the data for each factor at each geographic location changed monotonically and were in agreement with the global data in Figure 7b. At all locations, except Portland ME, ceiling insulation provided the greatest reduction in annual cooling. The solar reflectance of the roof, however, reduced annual cooling significantly. In fact, at all locations except Phoenix, the lowest annual cooling load was achieved at the highest value of solar reflectance. The reduction in annual cooling appears to be a linear effect of roof solar reflectance. It is interesting to note that if one neglects the uninsulated case, then the effect of solar reflectance provides the largest reduction in annual cooling loads. Increased levels of attic ventilation also decreased the annual cooling load, although to a lesser extent.

Annual Heating Load

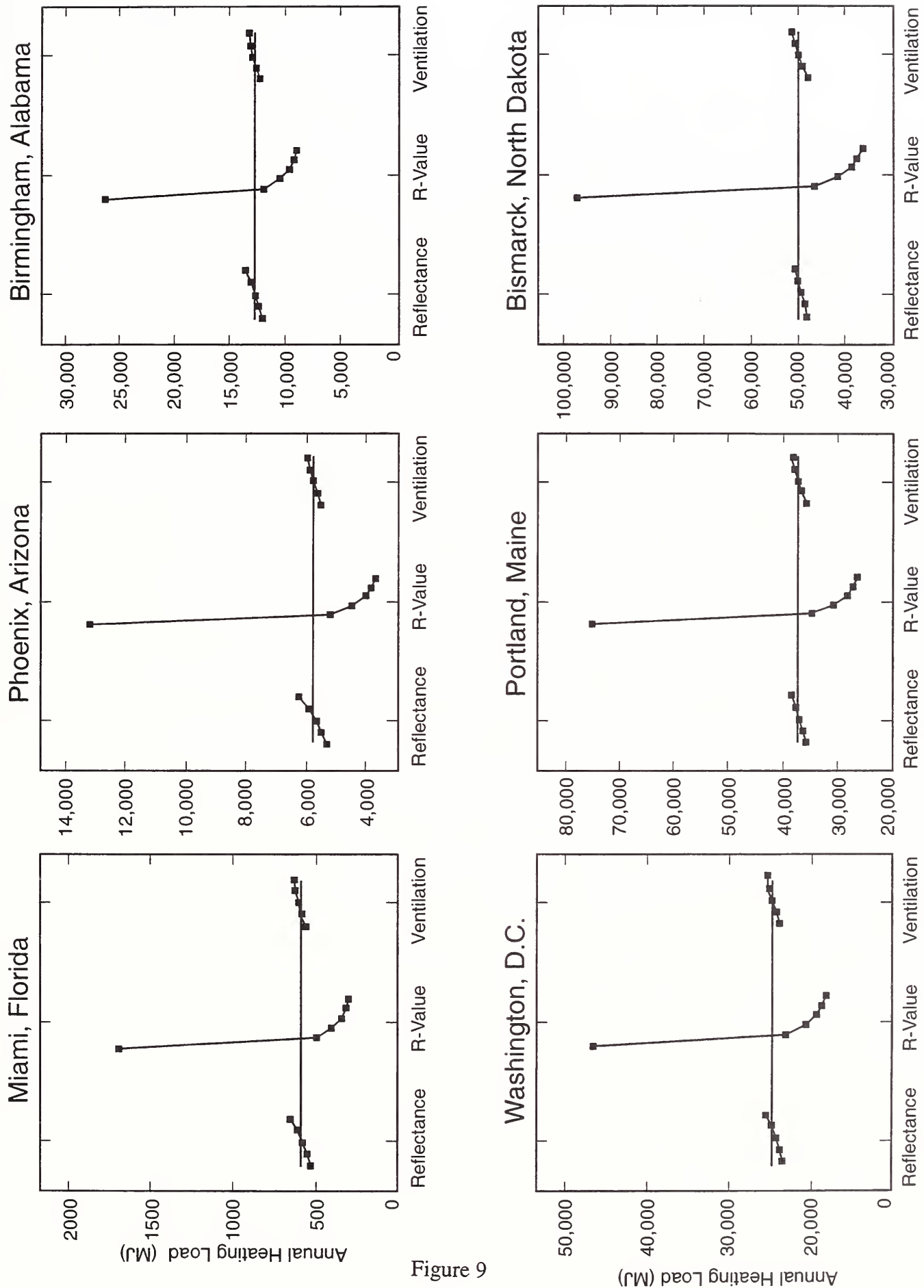


Figure 6

Annual Cooling Load

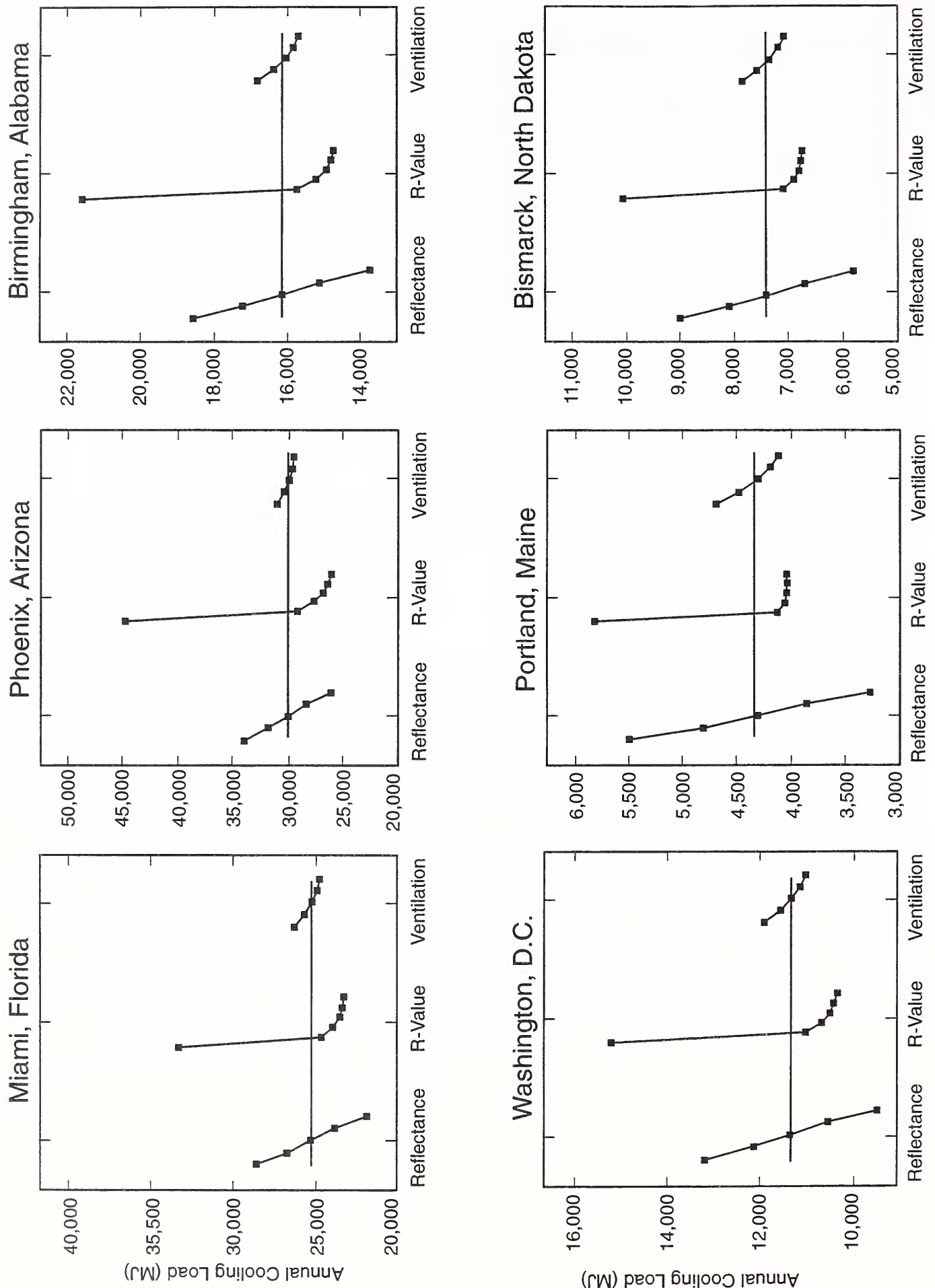


Figure 10

Peak Heating Load

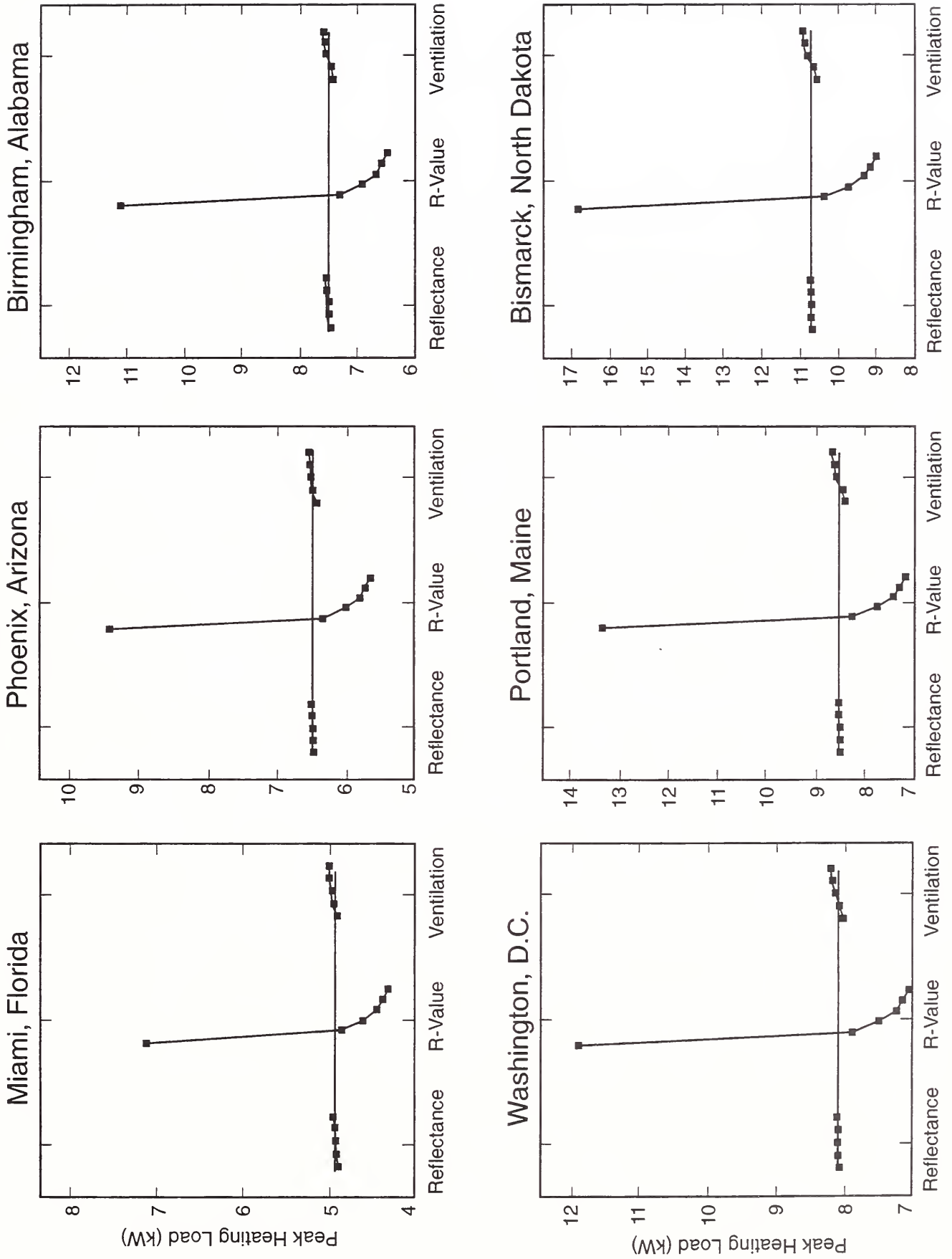


Figure 11

Peak Cooling Load

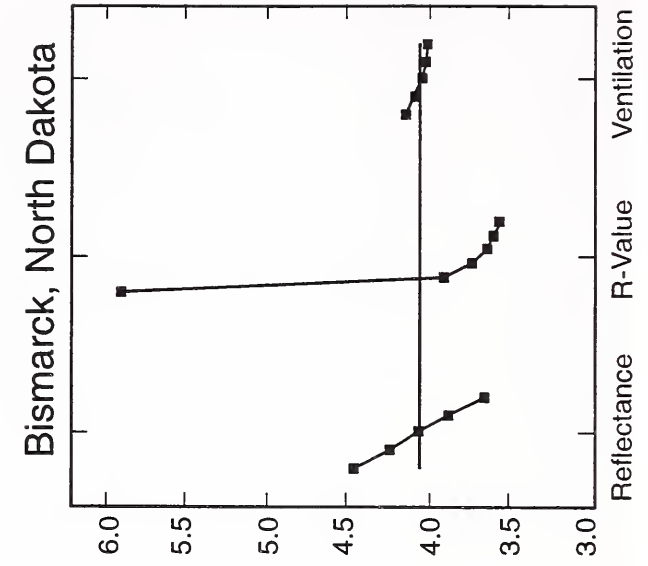
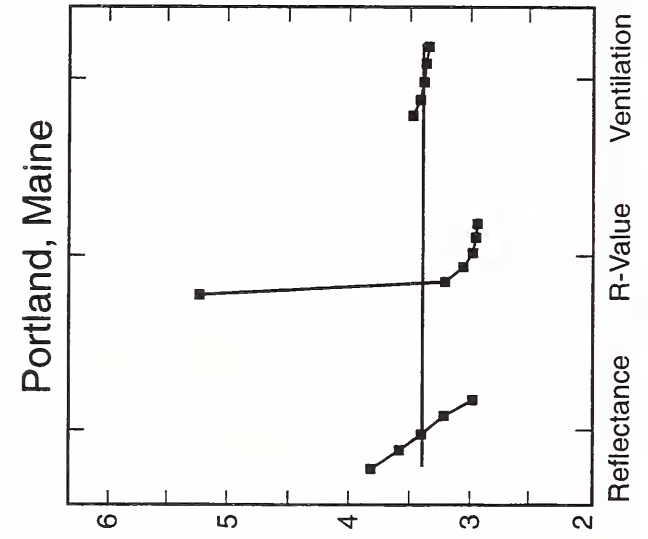
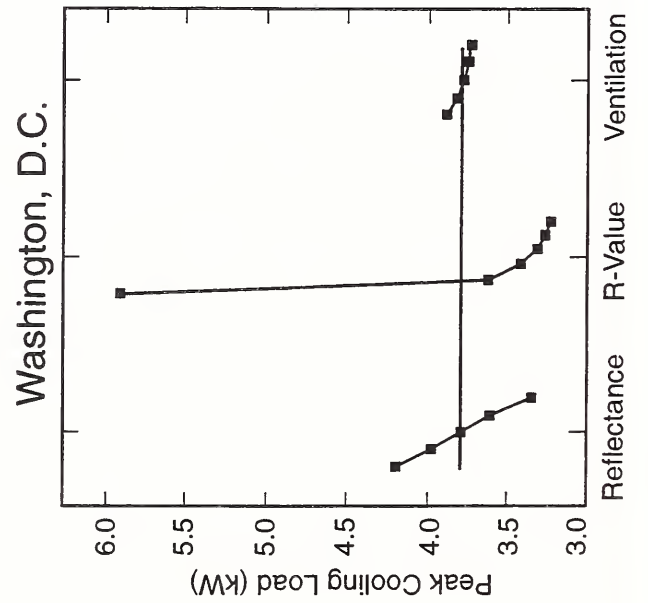
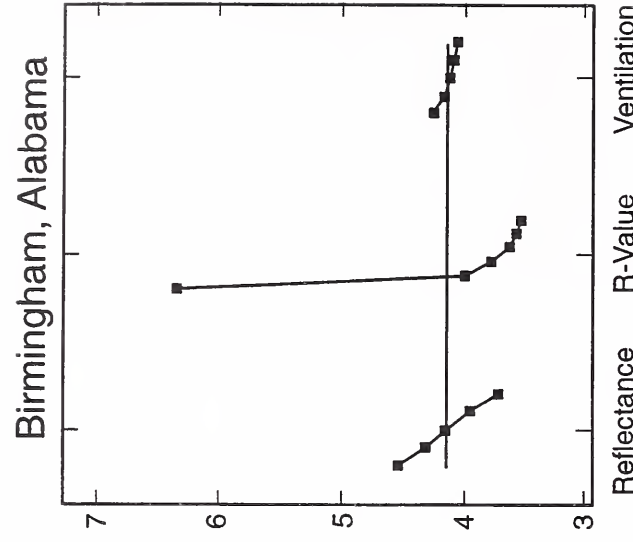
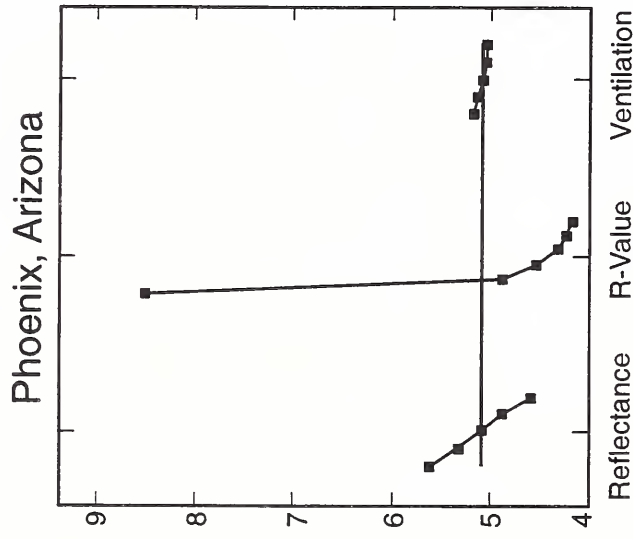
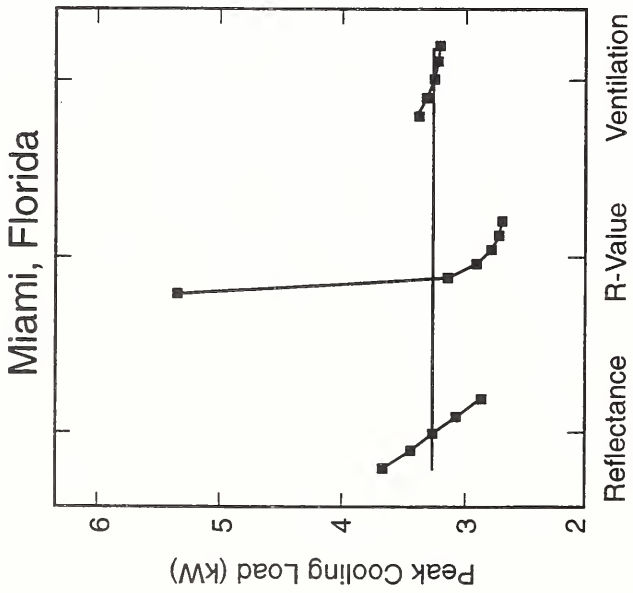


Figure 12

Figure 10 depicts somewhat peculiar results for Portland ME at high levels of ceiling R-value. At levels above $R-3.3 \text{ m}^2\cdot\text{K/W}$ ($R-19 \text{ ft}^2\cdot^\circ\text{F}\cdot\text{h/Btu}$), the annual cooling load increased slightly; meaning that external cooling (from the HVAC system) was required to remove the heat gain to the conditioned space. This seemingly unusual result was an artifact of the input parameters for the building and is discussed further in Building Loads Discussion. It should be re-stated that the model did not account for the (beneficial) effects of natural ventilation. Specifically, the analysis did not include a schedule for opening and closing of the windows. The author acknowledges that ordinarily the occupants, if home, would more than likely (although not necessarily) take advantage of natural ventilation for space cooling.

Hourly peak heating and cooling loads are illustrated in Figures 11 and 12, respectively. For peak heating (Figure 11), trends in the data for each city were very similar to the global trends illustrated in Figure 8a. In order of importance, the largest benefit resulted from increased levels of attic insulation. The effect of solar reflectance was inconsequential and increased levels of ventilation were detrimental (i.e., small increase in peak heating). For peak cooling (Figure 12), trends in the data for each city were again very similar to the global trends illustrated in Figure 8b. As observed before in Figure 8b, the factors affecting peak cooling in order of benefit were R-value, solar reflectance, and ventilation. The effects were beneficial, that is, higher levels reduced peak cooling requirements. Again, if one neglects the uninsulated case, then solar reflectance provides the largest reduction in peak cooling.

Table 11 summarize the optimum settings (levels) for each factor by city. A precautionary note is required so that the results are not misinterpreted. The dex-mean plot is an averaging tool, so ranking of optimum settings is only valid within a factor, not between factors. Generalizing that a specific level of one factor is better than a level of the other factors should not be attempted.

Table 11 Optimum Settings (Levels) for Building Loads (Annual and Hourly Peak)												
Geographic Location	ρ - Roof				Ceiling R-value				Attic Ventilation			
	Heating		Cooling		Heating		Cooling		Heating		Cooling	
	Ann.	Peak	Ann.	Peak	Ann.	Peak	Ann.	Peak	Ann.	Peak	Ann.	Peak
1. Miami, FL	1	1	5	5	6	6	6	6	1	1	5	5
2. Phoenix, AZ	1	1	5	5	6	6	6	6	1	1	5	5
3. Birmingham,	1	1	5	5	6	6	6	6	1	1	5	5
4. Washington,	1	1	5	5	6	6	6	6	1	1	5	5
5. Portland, ME	1	1	5	5	6	6	3*	6	1	1	5	5
6. Bismarck,	1	1	5	5	6	6	6	6	1	1	5	5

* Anomalous result as described in text.

The results in Table 11 are consistent with engineering expectations, as well as previous results published in the literature (Griggs and Courville 1989, Parker et al. 1998). In general, the best settings for heating (annual and peak) are low solar reflectance, high ceiling thermal resistance, and low ventilation rates for the attic¹. For cooling, the best settings are high solar reflectance, high ceiling thermal resistance, and high ventilation rates for the attic. What is particularly powerful is that these settings are (globally) consistent, as shown above, across a wide range of geographical locations (and therefore climatic conditions) in the contiguous U.S. The effects for solar reflectance (as well as ventilation) are diametrically opposite for heating and cooling. Thus, for heating, a low-reflectance (i.e., black) roof is best, and for cooling a high-reflectance (i.e., white) roof is best. Since current technologies at present do not permit a roof with both levels, what is required is an analysis of economic trade-offs (i.e., cooling benefit versus heating penalty) covered in Economic Discussion.

Effect of Solar Reflectance on Predicted Annual Loads (Heating and Cooling)

In order to determine the effect of roof solar reflectance and ceiling R-value on the annual heating and cooling loads, a subset of the data presented in Figures 9 to 12 was examined. The attic ventilation rate was fixed at the lowest setting (0.5 air changes per hour) and the attic mass framing area fixed at the mid-value of 38.7 m² (Table 7). For each location, the annual load in MJ was plotted on the y-axis and solar reflectance on the x-axis. The effect of ceiling R-value was treated parametrically and varied from "none" (i.e., uninsulated) to R-8.6 m²·K/W (R-49 ft²·°F·h/Btu) following the levels described in Table 7. Figures 13 to 18 illustrate the annual heating loads and annual cooling loads for Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck.

A discussion of Figure 13 for Miami will serve as a useful example for the other cities (Figures 14 to 18). Figures 13a and 13b plot the annual heating and cooling loads, respectively, versus the roof solar reflectance over the range 0.10 to 0.80 at the levels shown in Table 7. Parametric values for ceiling R-values ranged from "none" (uninsulated case) to R-8.6 m²·K/W (R-49 ft²·°F·h/Btu) and are identified by line-type in the plot. In Figure 13a, the annual heating load increased nonlinearly as the solar reflectance increased. For a fixed level of ceiling R-value, the largest increase in annual heating was for an uninsulated attic. As before, a substantial reduction in the annual heating and cooling loads was noted between the uninsulated case and the level of R-1.9 m²·K/W (R-11 ft²·°F·h/Btu). In Figure 13b, the annual cooling load decreased linearly as the solar reflectance increased. In fact, for a particular level of ceiling R-value, the annual cooling load requirement was minimized at the highest level of the roof solar reflectance. The slope for the line, however, was less pronounced for higher levels of ceiling R-value. The greatest reduction in annual cooling load was for an uninsulated attic. It is interesting to note that the lines seem to converge at higher levels of solar reflectance (Figure 13b).

¹Note that factors other than energy considerations such as moisture control are generally more important in determining the proper or appropriate levels of attic ventilation. The analysis presented here is strictly based on energy efficiency.

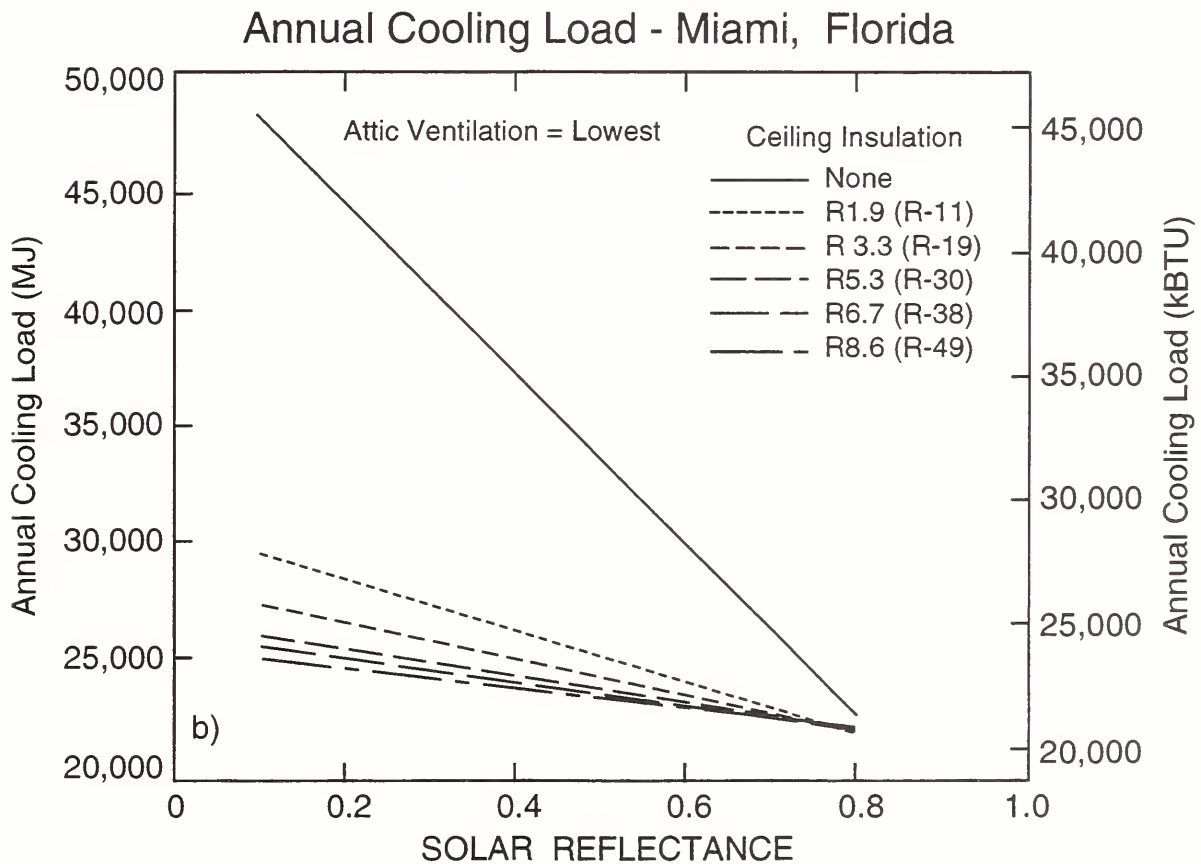
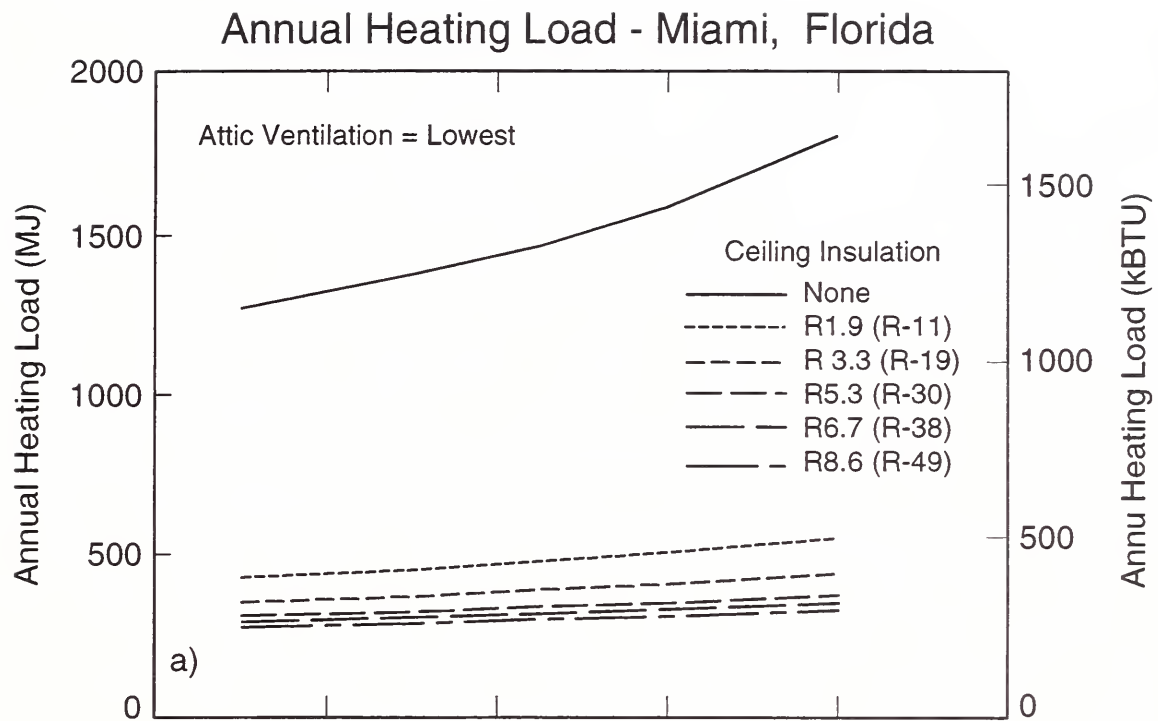
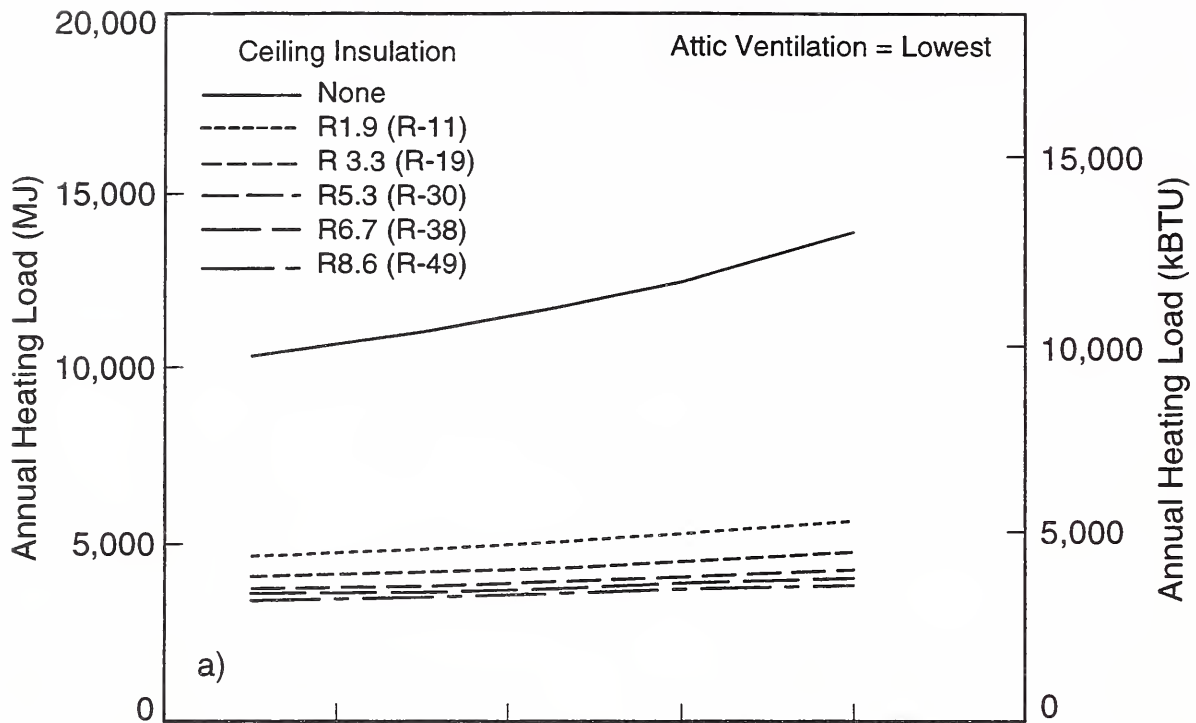


Figure 13

Annual Heating Load - Phoenix, Arizona



Annual Cooling Load - Phoenix, Arizona

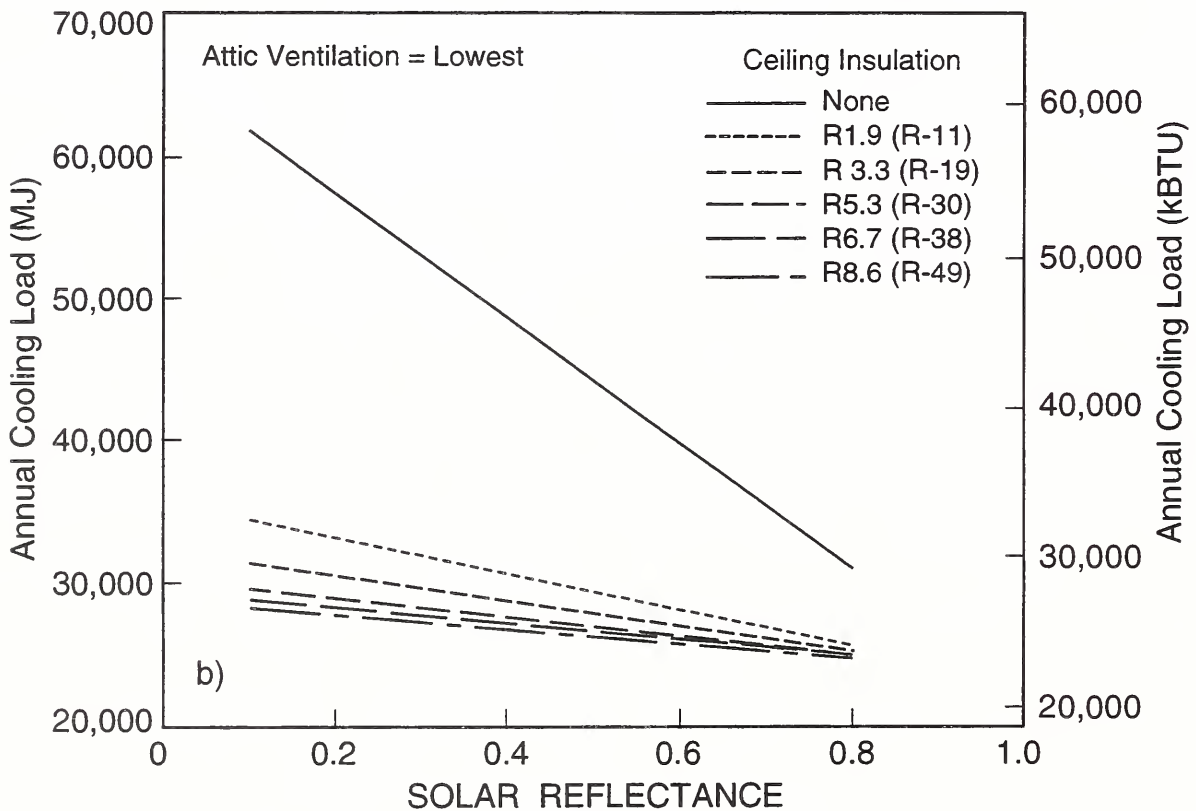
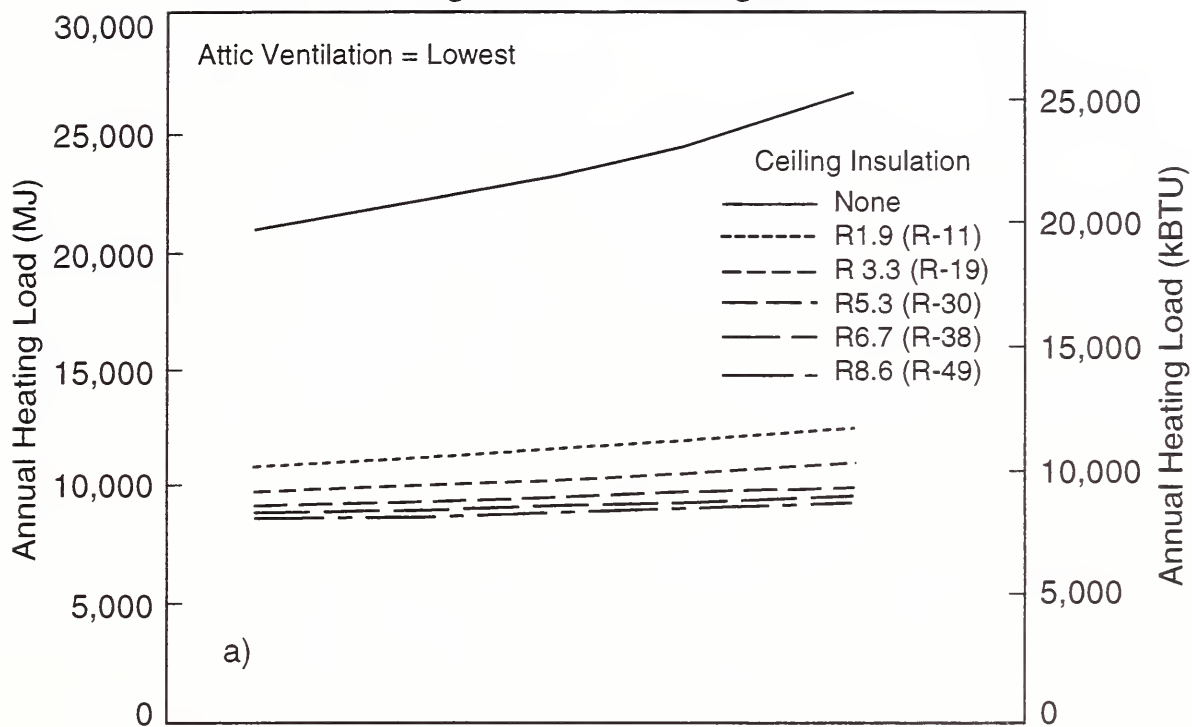


Figure 14

Annual Heating Load - Birmingham, Alabama



Annual Cooling Load - Birmingham, Alabama

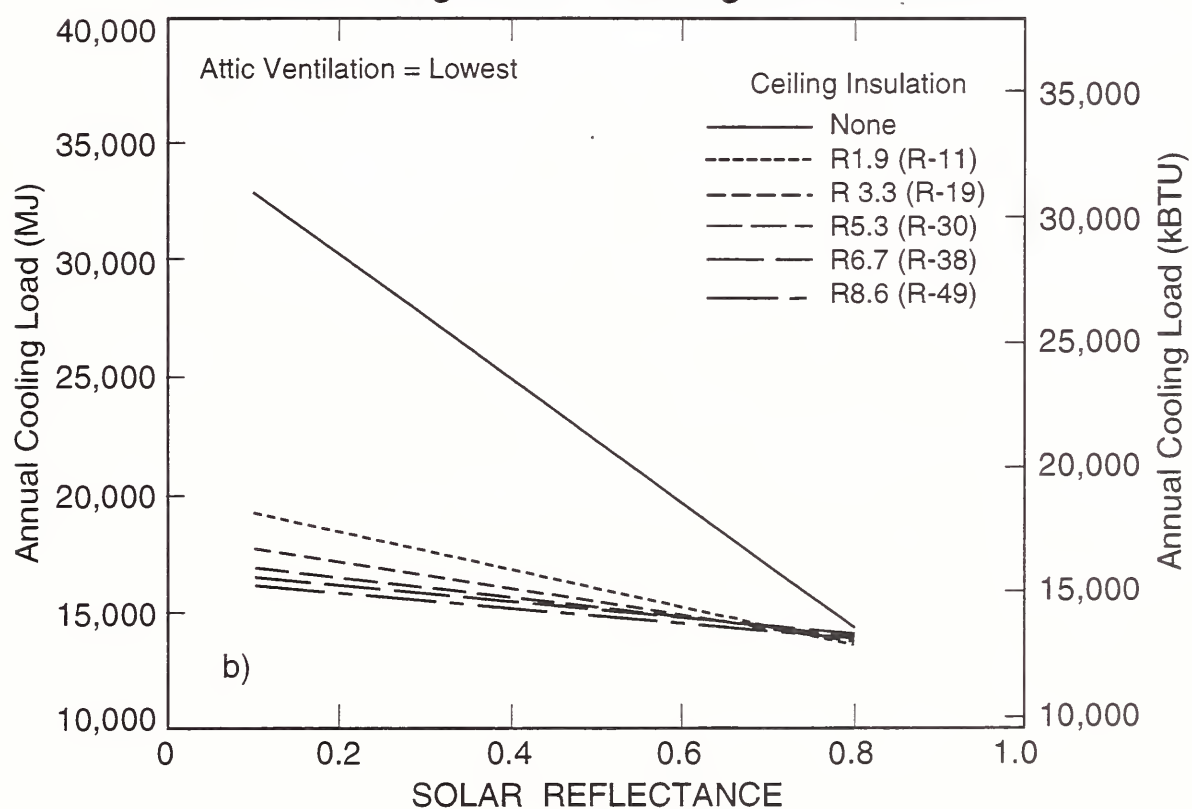


Figure 15

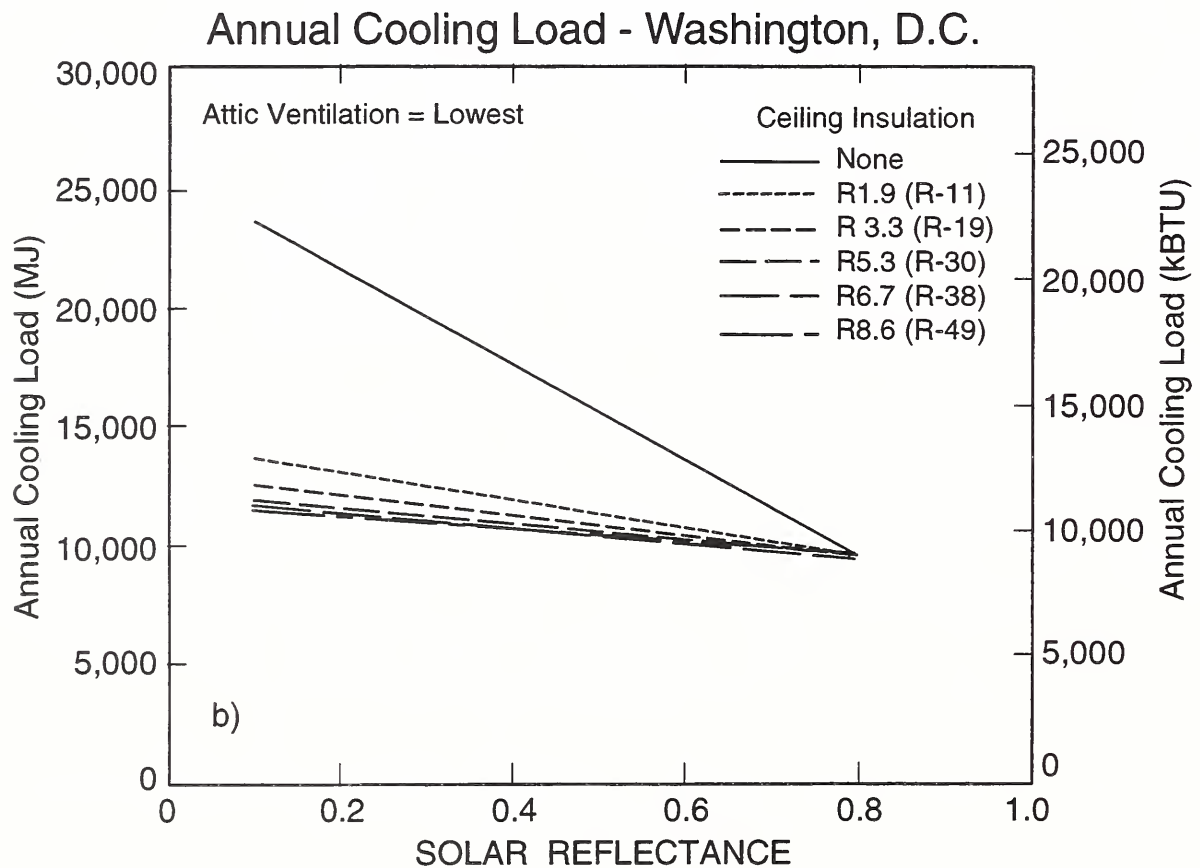
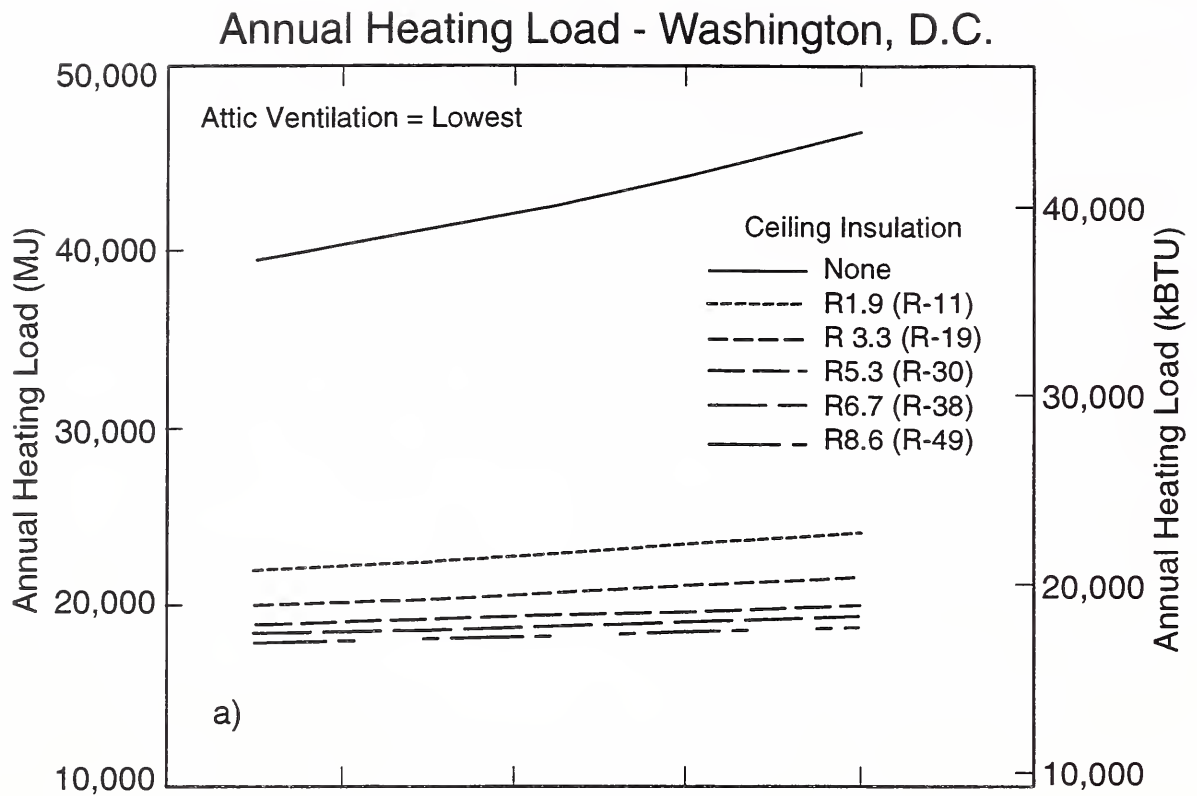


Figure 16

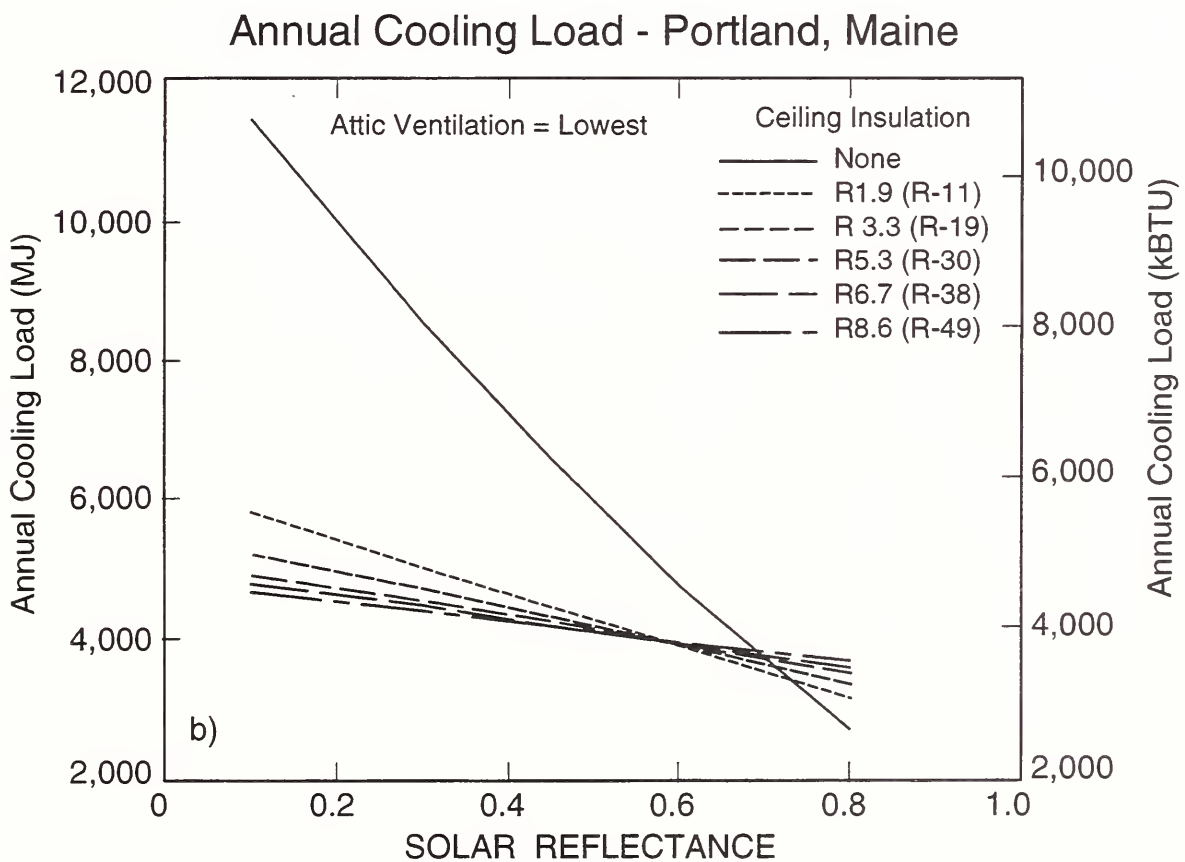
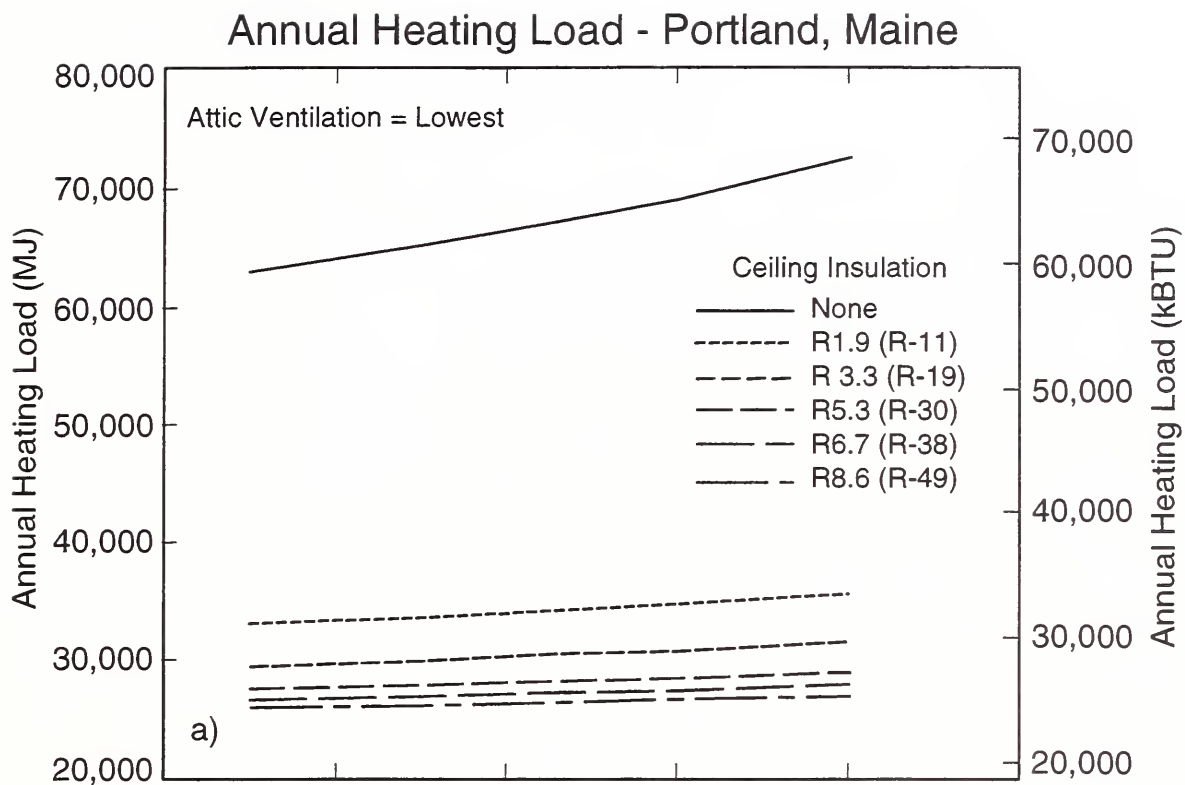
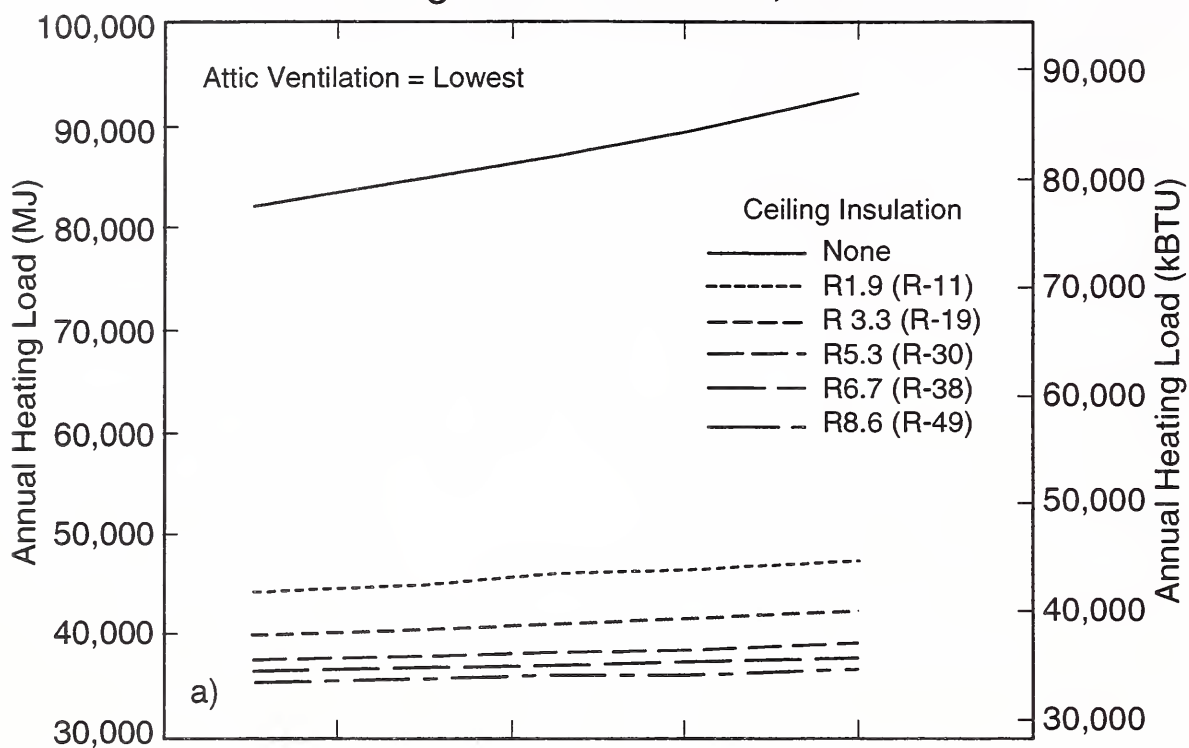


Figure 17

Annual Heating Load - Bismarck, North Dakota



Annual Cooling Load - Bismarck, North Dakota

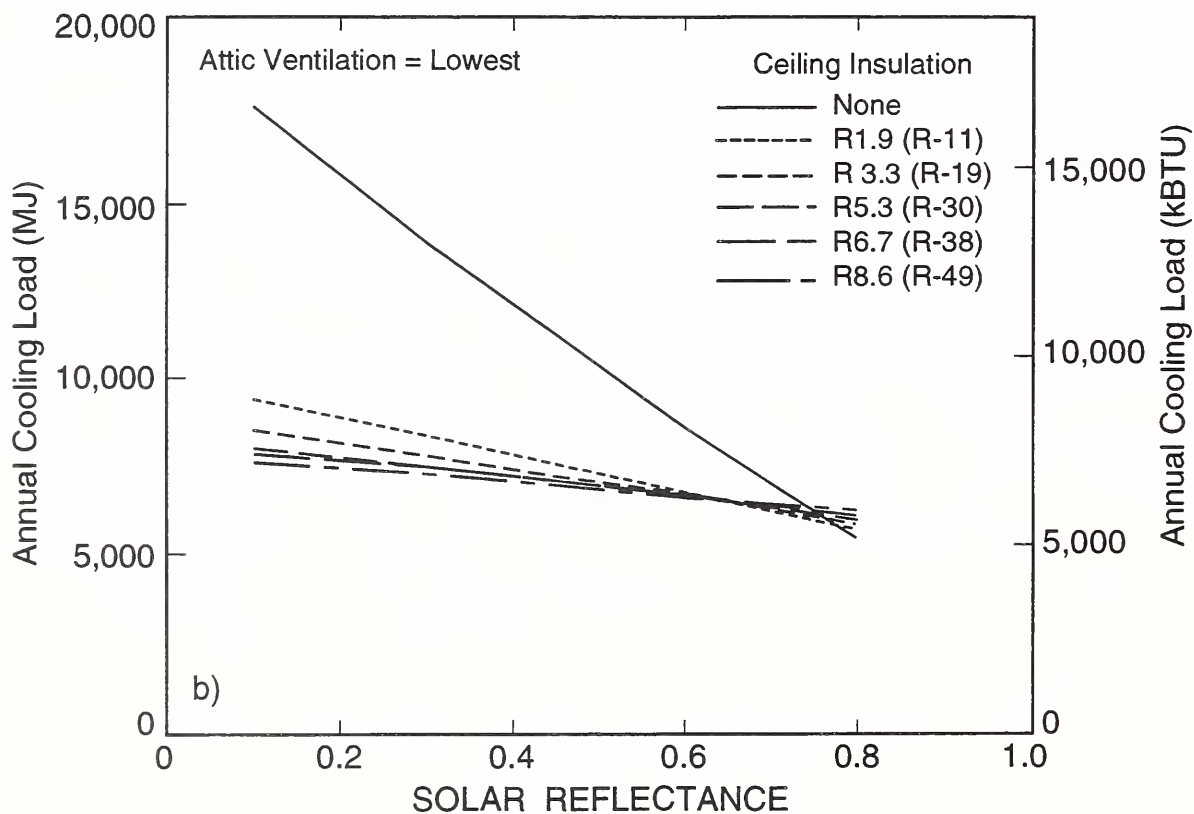


Figure 18

An examination of the other cities (Figures 14 to 18) revealed results consistent with the trends observed for Miami, and the global plots above. Note that for Portland ME and Bismarck (Figures 17 and 18, respectively), anomalous annual cooling loads were obtained at high levels of roof solar reflectance and ceiling R-values due to the removal of internal heat gains. As mentioned, these results are largely an artifact of the input parameters for the model and are discussed further in Building Loads Discussion. In general, however, for any given level of attic insulation, higher levels of solar reflectance caused an undesired increase in the annual heating load and a beneficial decrease in the annual cooling load. Of particular interest is whether the benefits from lower annual cooling outweigh the detrimental increase in annual heating. This will be discussed further in Economic Discussion.

Effect of Solar Reflectance on Predicted Hourly Peak Loads (Heating and Cooling)

Figures 19 to 24 show the hourly peak heating and cooling loads for each city as a function of solar reflectance and different levels of ceiling R-value. Like the previous plots for annual loads, the attic ventilation rate was fixed at the lowest level (see Table 7), the attic mass framing area at Level 2, and the solar reflectance and ceiling R-value ranged from their respective minimum to maximum levels. In general, the results are consistent with the global plots for peak heating (cooling) loads presented in Figures 11 and 12, respectively. For peak heating loads, increasing levels of solar reflectance were essentially inconsequential (Figures 19a to 24a). For peak cooling loads, however, the roof solar reflectance resulted in a linear reduction of peak cooling loads (Figures 19b to 24b). Thus, for any given level of ceiling R-value, the hourly peak cooling load requirement was minimized at the highest level of the roof solar reflectance. The slope of the line, however, was less pronounced for higher levels of ceiling R-value. The greatest reduction in the hourly peak cooling load was for the case of an uninsulated attic. Again, it is interesting to note that the lines tend to converge at high levels of roof solar reflectance. From a demand point-of-view, it would seem that high levels of roof solar reflectance could be quite beneficial for a residence.

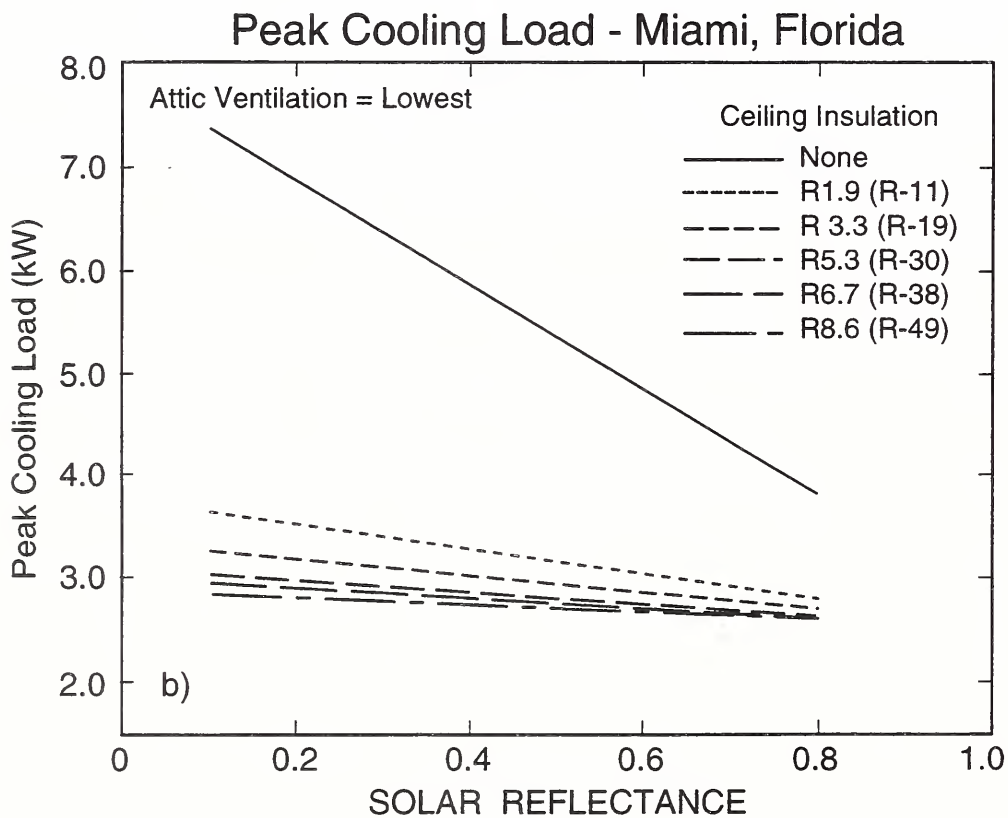
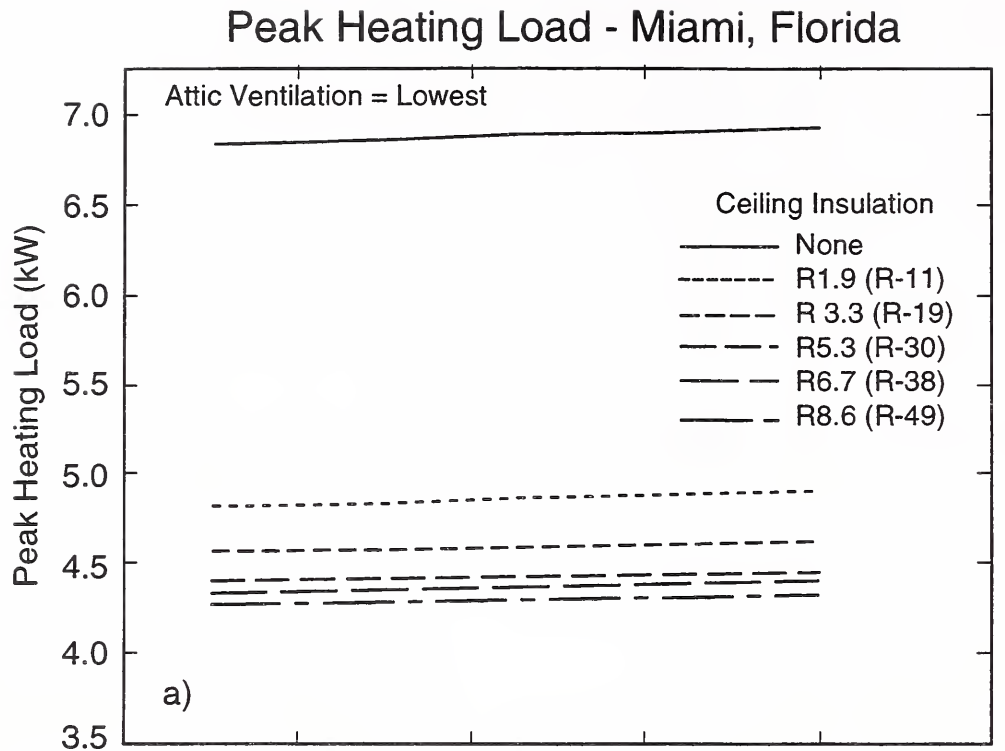
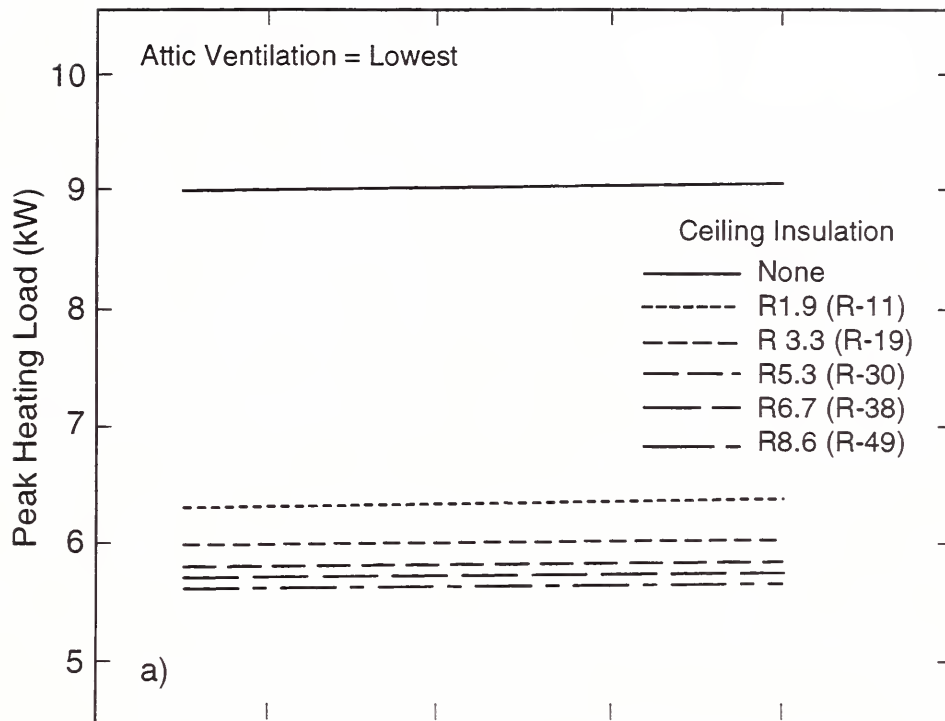


Figure 19

Peak Heating Load - Phoenix, Arizona



Peak Cooling Load - Phoenix, Arizona

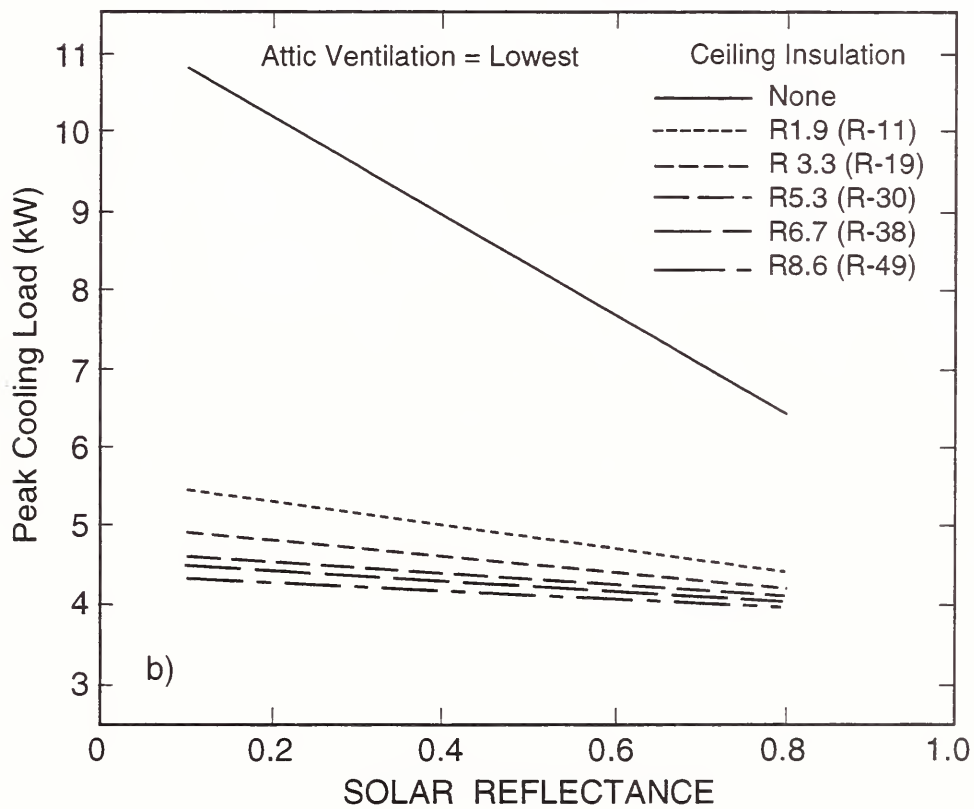
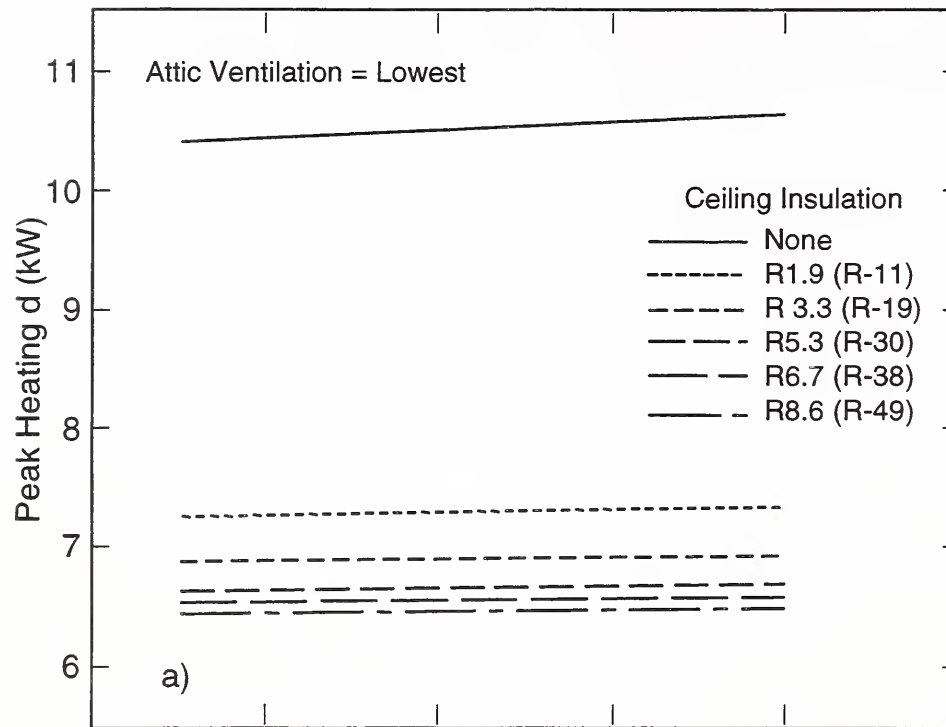


Figure 20

Peak Heating Load - Birmingham, Alabama



Peak Cooling Load - Birmingham, Alabama

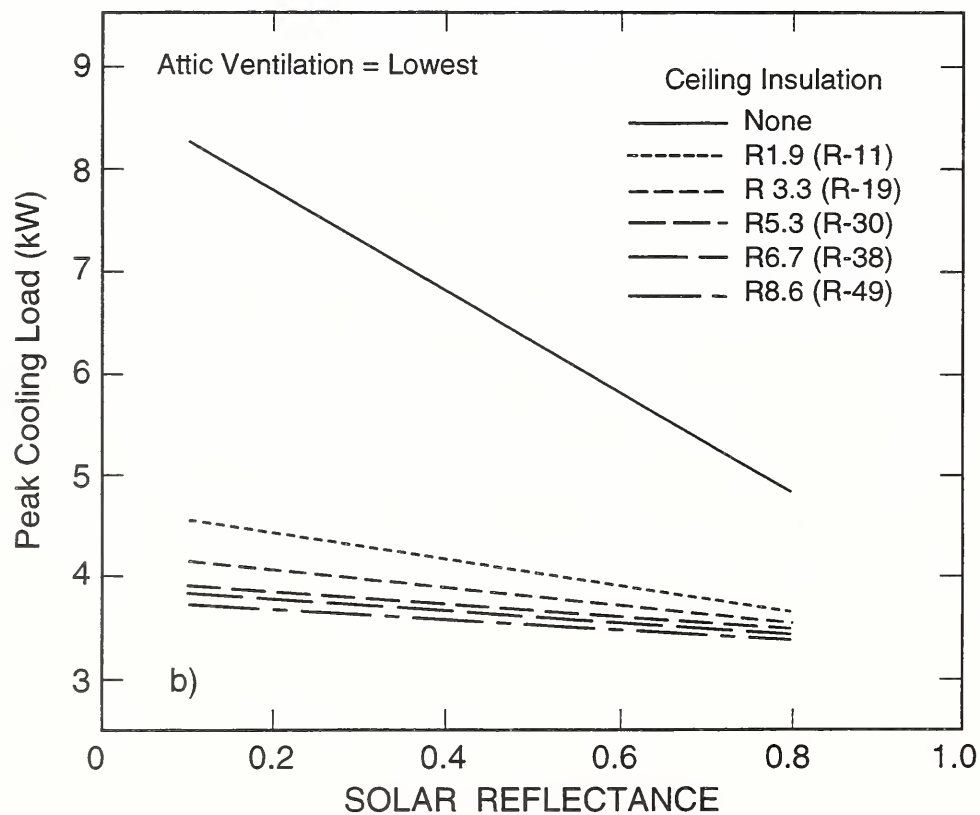
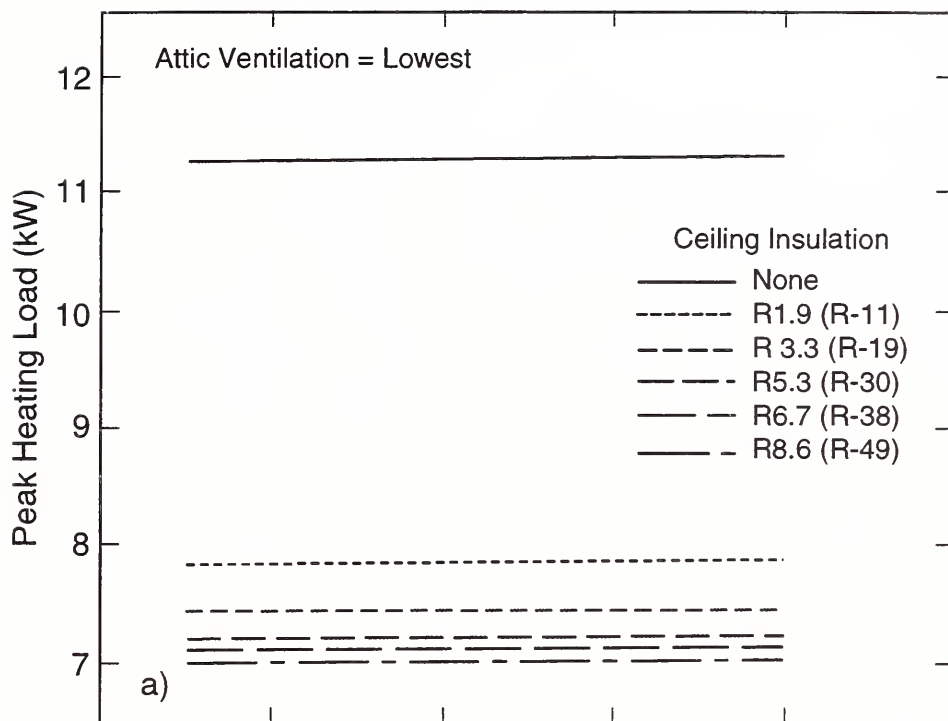


Figure 21

Peak Heating Load - Washington, D.C.



Peak Cooling Load - Washington, D.C.

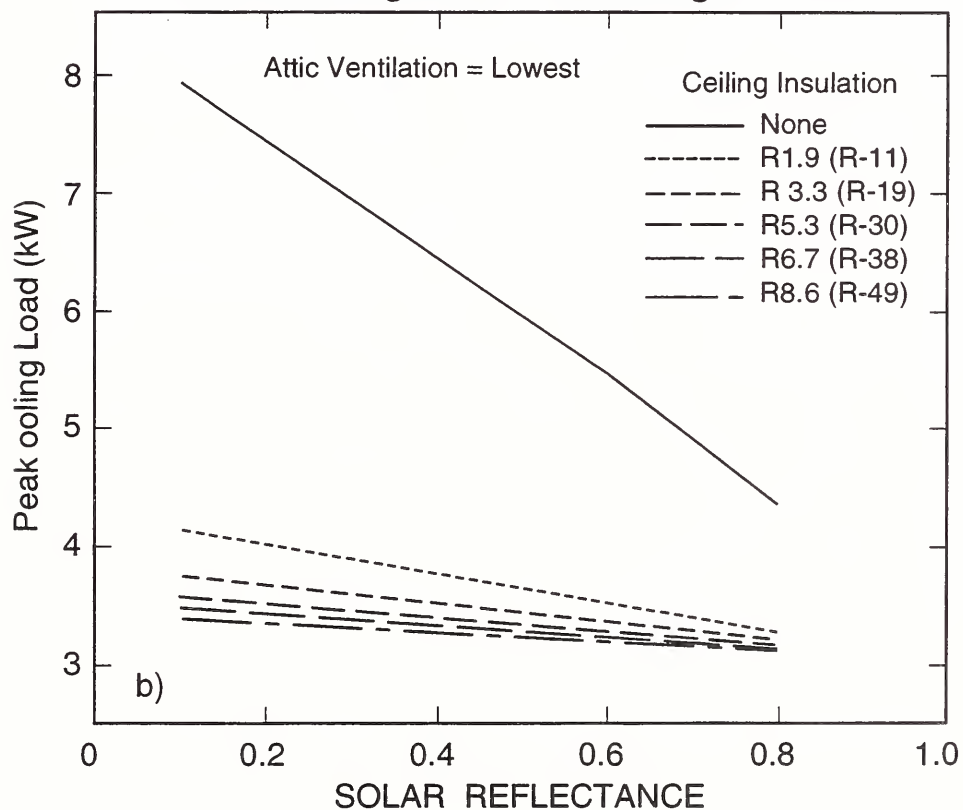
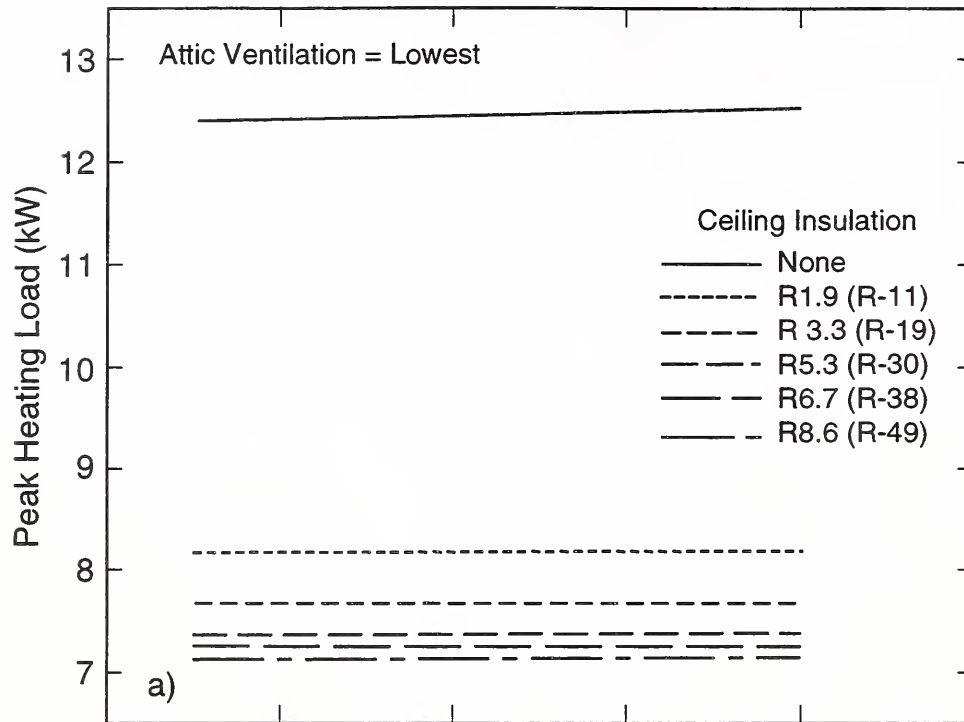


Figure 22

Peak Heating Load - Portland, Maine



Peak Cooling Load - Portland, Maine

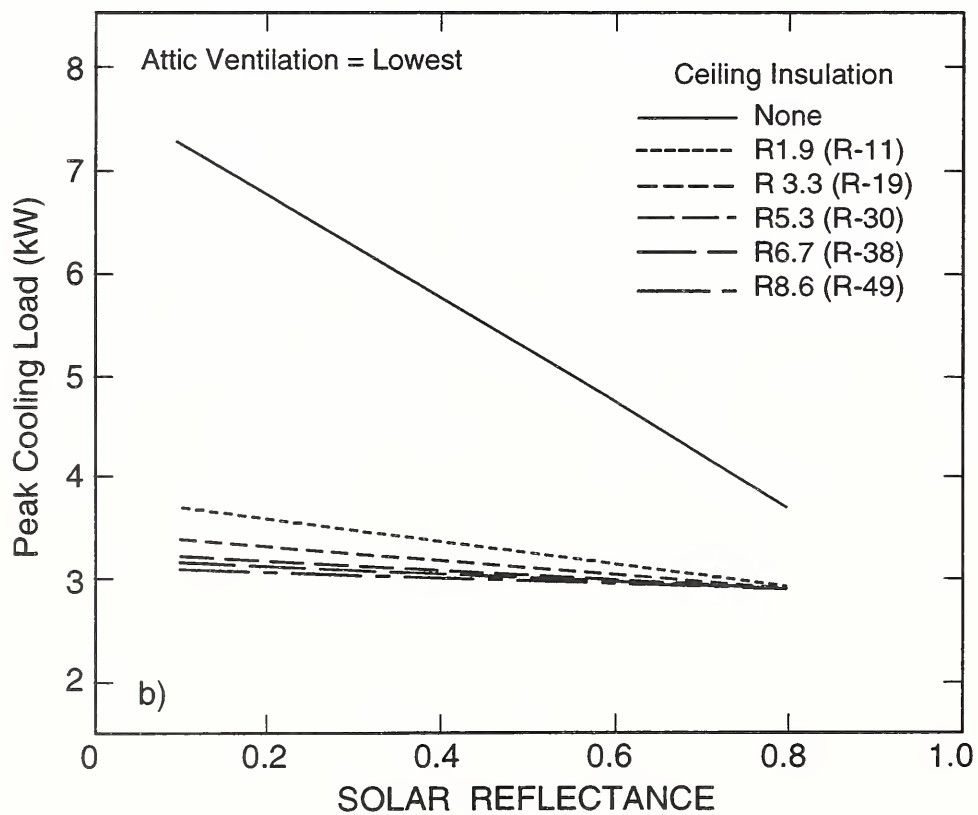
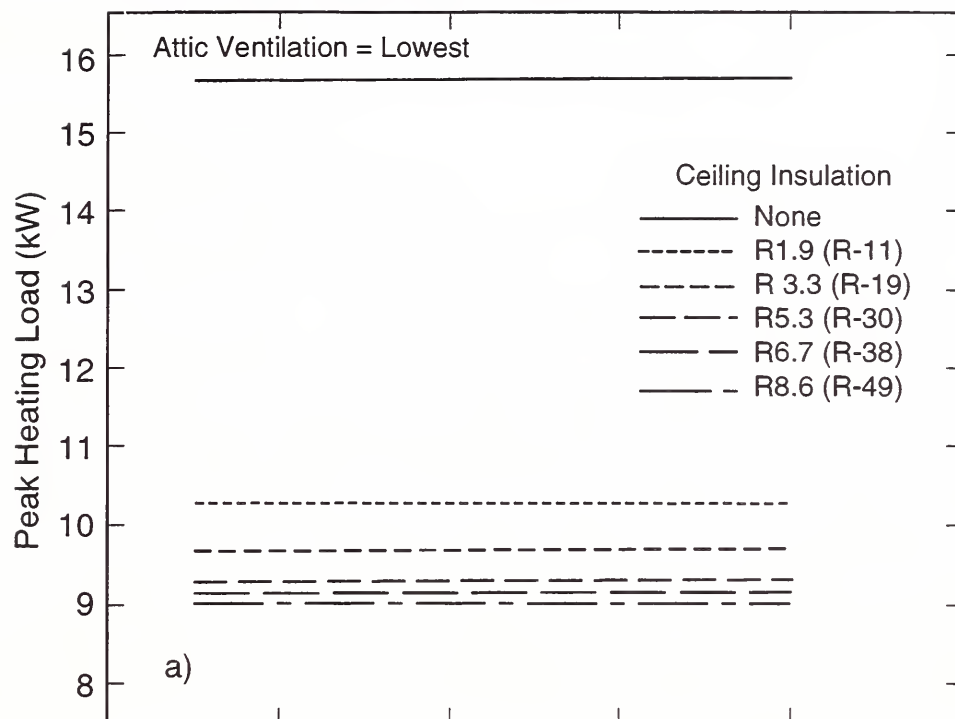


Figure 23

Peak Heating Load - Bismarck, North Dakota



Peak Cooling Load - Bismarck, North Dakota

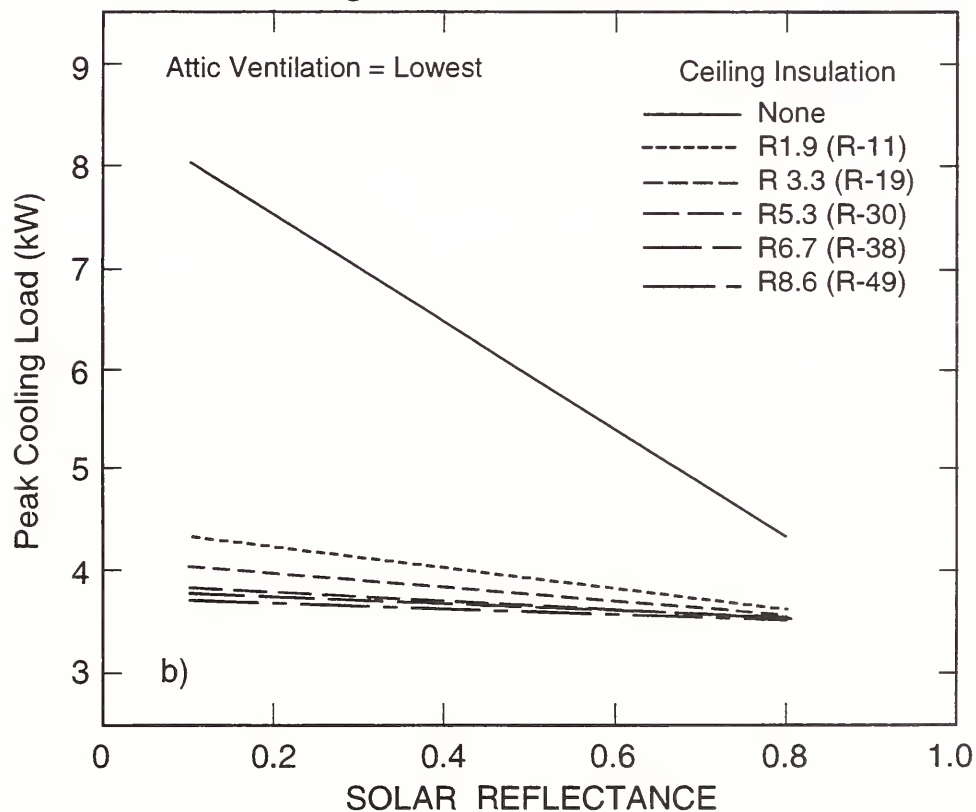


Figure 24

BUILDING LOADS DISCUSSION

This section presents an analysis of residential building loads under steady ambient conditions in order to provide further insight for the predicted results for the 2700 simulation runs.

Test Conditions

As mentioned earlier, TARP has the capability to determine heating and cooling requirements for a conditioned space for a single "design day." Two new environment input files were prepared for heating and cooling that specified fixed ambient temperatures of -1.1°C (30°F) and 26.7°C (80°F), respectively. A clear sky condition was selected and a geographic location 40 degrees latitude and 90 degrees longitude (near Springfield, Illinois) was selected arbitrarily. The annual ground temperature for this location was obtained from Kusuda (1981). The date for the analysis was chosen as 21 September to provide equal parts of daylight and night. A transient solar profile was provided by a built-in function of TARP and the proportion of solar beam and diffuse radiation was determined by a correlation function. Examples of the input files are presented in Appendix C.

Test Plan

The experimental plan was a full factorial design for the three factors shown in Table 12. The total number of runs is 12 ($=2 \times 3 \times 2$). The roof solar reflectance was varied at 3 levels from 0.1 to 0.8 and the ceiling R-value was varied at one of two values; either "none" (uninsulated attic) or $R-6.7 \text{ m}^2\cdot\text{K}/\text{W}$ ($R-38 \text{ ft}^2\cdot^{\circ}\text{F}\cdot\text{h}/\text{Btu}$). The attic ventilation rate and mass framing area were fixed at 0.5 air changes per hour and 38.7 m^2 (417 ft^2) (see Table 7). All other input factors - site and shading, interior thermostat settings, internal load, etc. - were the maintained at the same settings as the previous simulation runs (see Residential Models).

Table 12 Factor and Levels for Constant Ambient Test Conditions	
1	Ambient air temperature (environmental input) - 2 levels: a) -1.1°C , 26.7°F b) 30°C , 80°F
2	Roof solar reflectance (ρ) - 3 levels: 0.10, 0.45, 0.80
3	Ceiling thermal resistance (R-value) - 2 levels: a) none, $6.7 \text{ (m}^2\cdot\text{K}\cdot\text{W}^{-1}\text{)}$ b) none, $38 \text{ (h}\cdot\text{ft}^2\cdot^{\circ}\text{F}\cdot\text{Btu}^{-1}\text{)}$

Effect of Roof Solar Reflectance on Building Loads

For each run, two response variables were determined: heating and cooling load. Figure 25 plots the predicted loads for both heating and cooling as a function of roof solar reflectance under constant ambient temperature conditions. The effect of ceiling R-value was treated parametrically and varied from “none” (i.e., uninsulated attic) to $R-6.7 \text{ m}^2\cdot\text{K/W}$ ($R-38 \text{ ft}^2\cdot^\circ\text{F}\cdot\text{h/Btu}$). The trends in Figure 25 for heating and cooling are quite similar to those observed in Figures 13 through 18 for annual loads. In general, at higher values of roof solar reflectance, the heating load increased and, conversely, the cooling load decreased. Note that for cooling, the loads for the insulated ($R-6.7 \text{ m}^2\cdot\text{K/W}$ [$R-38 \text{ ft}^2\cdot^\circ\text{F}\cdot\text{h/Btu}$]) attic and uninsulated case cross over at values of roof solar reflectances of $\rho \geq 0.7$. As mentioned earlier, this condition seems somewhat counter-intuitive and was investigated further.

For a roof solar reflectance of 0.8, the hourly profiles for the cooling load, attic air temperature, and outside heat flux for the south face of the roof are plotted in Figure 26 for the insulated and uninsulated cases. In Figure 26a, note that the hourly cooling load for the uninsulated case is greater than the insulated case only for the hours of 09:00 (9AM) to 19:00 (7PM), essentially the sunlit hours of the cycle. During the rest of the diurnal cycle (night hours), the cooling load for the uninsulated case is less than the insulated case. In fact, for the hours 03:00 (3AM) to 06:00 (6AM), the hourly cooling load for the uninsulated case is zero - no cooling required. The net difference between the curves represents the difference in cooling loads observed in Figure 25 at $\rho = 0.8$. Additional insight is provided by Figures 26b and 26c, which show that the ambient air temperature and heat flux of the outside south roof face are also greater for the uninsulated case for most of the diurnal cycle.

The results shown in Figure 26 are indicative of night-time radiative cooling of the structure. Essentially, the building's exterior surfaces “see” a clear-sky effective temperature of 13°C (55°F), as determined in the simulation by TARP. Heat conducted through the building envelope warms the exterior surfaces resulting in long-wave radiation exchange with the clear-sky. An increase in the temperature of the exterior surface increases the radiant heat exchange with the surroundings. This effect is illustrated in Figures 26b and 26c. Recall that the thermostat for the interior space is maintained at 25.6°C (78°F) under cooling conditions. At night, the heat loss through the ceiling warms the attic air. For the uninsulated case, the air temperature is approximately 1.5°C (2.7°F) greater than the insulated case during the night hours (Figure 26b). This elevated attic air temperature warms the roof and results in an increase in the outside heat flux of the roof (Figure 26c). The presence of the ceiling insulation reduces the effect of night-time radiative cooling.

Figure 26 shows two counter effects, radiative cooling of the roof during night hours and solar gain during sunlit hours. For the given inputs to the model it would seem, as evident above and in the previous plots (Figures 13 through 18), that radiative cooling is important for the simulations presented in this report, particularly at higher values of roof solar reflectance. This may not be the case, however, if the inputs to the model were changed or modified. For example, the thermostat control of most residential buildings, in practice is probably set lower than the prescribed value of 25.6°C (78°F) given in ASHRAE 90.2-1993 (ASHRAE 1993). As a check, the thermostat setting for cooling was reduced to 21.1°C (70°F) and the above runs repeated; all other conditions the same.

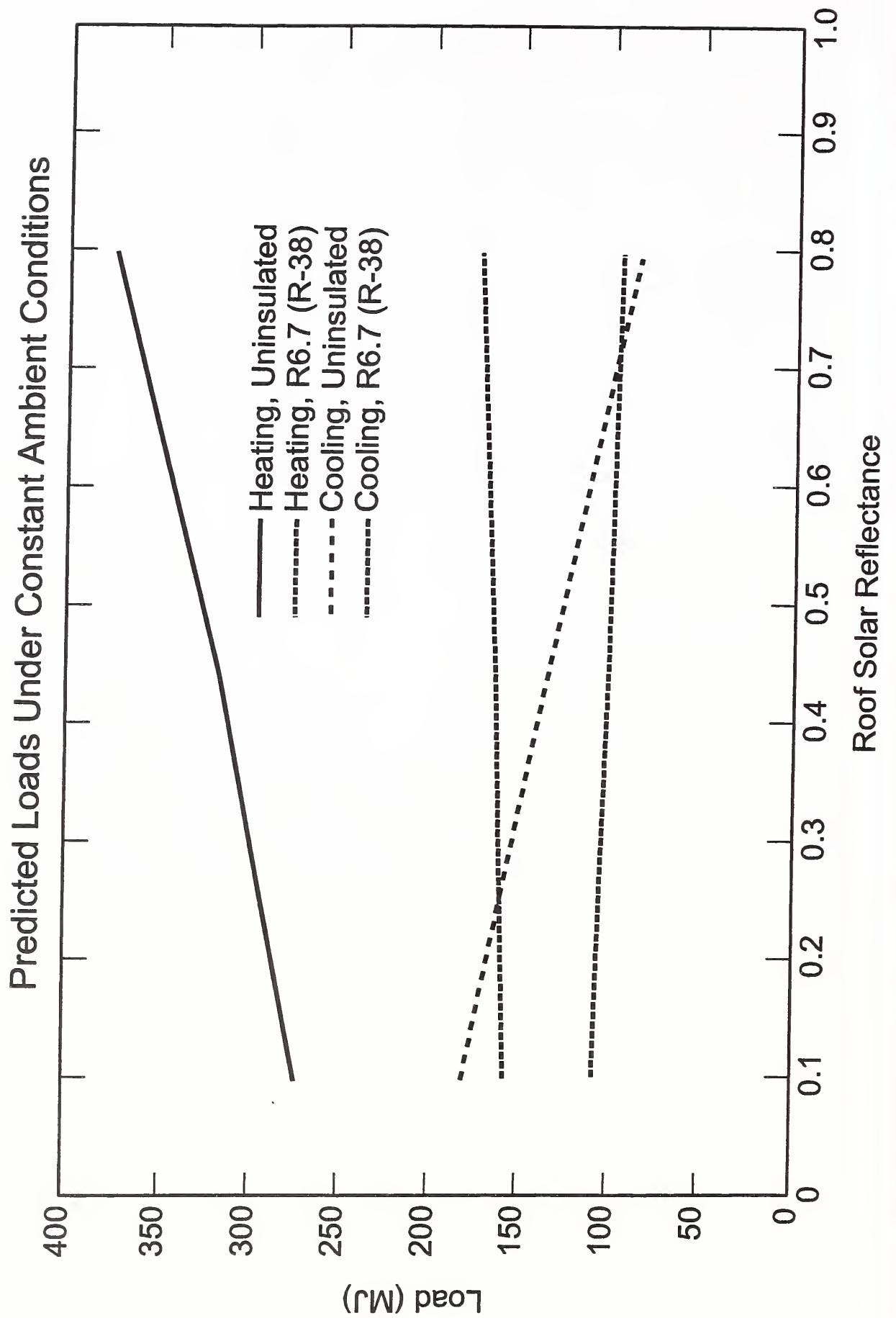


Figure 25

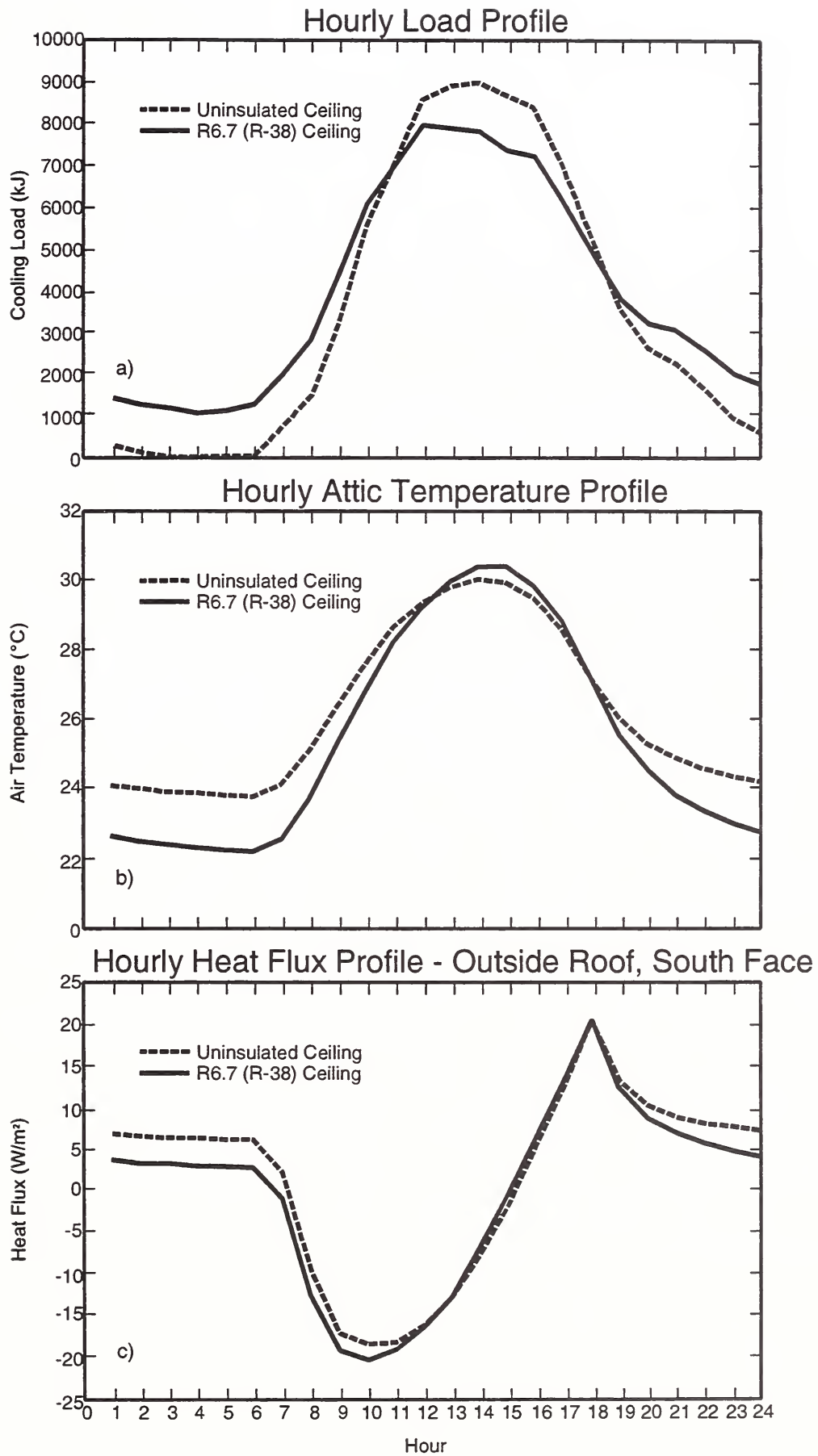


Figure 26

The resulting predicted cooling loads for uninsulated and insulated cases did not intersect as noted above in Figure 25.

ROOF TEMPERATURES

Additional computer simulations were conducted for each geographic location to provide predicted exterior temperatures of the roof surface at hourly intervals. Again, one year (8760 hours) of input WYEC weather data was utilized. However, in these runs, the TARP models were modified to provide hourly output of the exterior roof temperatures. Because of the large amount of output data, the test plan was limited to only 30 simulation runs. The predicted temperatures are presented graphically as described below.

Test Plan

The experimental plan was a full-factorial design for the two factors shown in Table 7. The full factorial design consisted of all possible combinations of levels of the two factors, so the total number of runs is 30 ($=6 \times 5$). For each geographic location, the primary factor, roof solar reflectance, was varied at 5 levels from 0.1 to 0.8. The ceiling insulation levels were set to their respective "base case" values of $R-5.3 \text{ m}^2\text{K/W}$ ($R-30 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F/Btu}$) for Miami and $R-6.7 \text{ m}^2\text{K/W}$ ($R-30 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F/Btu}$) for all other locations. The attic ventilation rate was fixed at a low constant rate of 0.5 air changes per hour for all simulation runs.

Table 13
Factor and Levels for Exterior Roof Temperature Analysis

1	Geographic location (city) - 6 levels: 1) Miami FL, 2) Phoenix AZ, 3) Birmingham AL, 4) Washington DC, 5) Portland ME, 6) Bismarck ND
2	Roof solar reflectance (ρ) - 5 levels: 0.10, 0.30, 0.45, 0.60, 0.80

Effect of Solar Reflectance on Roof Temperature

The effect of solar reflectance on the exterior roof temperatures was investigated using graphical analysis commonly known as a box plot. Figure 27 shows a series of box plots for each city. Each box plot represents a statistical summary by percentile of 8760 hours of temperature data for one simulation run. In other words, the temperature data has been mapped to a percentile basis from 0 to 100 (minimum predicted temperature to maximum) and plotted on that basis. For each city, the exterior temperature of the roof is plotted on the y-axis and the five levels of solar reflectance, on the x-axis. The box plot for each simulation of 8760 hours is constructed as follows: the bottom tic is the minimum temperature (of the simulation); the lower solid circle is the estimated 5 % point; the bottom of the box is the estimated 25 % point; the \times is the median (50 %); the top of the box is the estimated 75 % point; the upper solid circle is the estimated the 95 % point; and, the upper tic is the maximum temperature. So, for example, the 95 % point means that approximately 95 % of the 8760

Box Plot Roof Temperatures

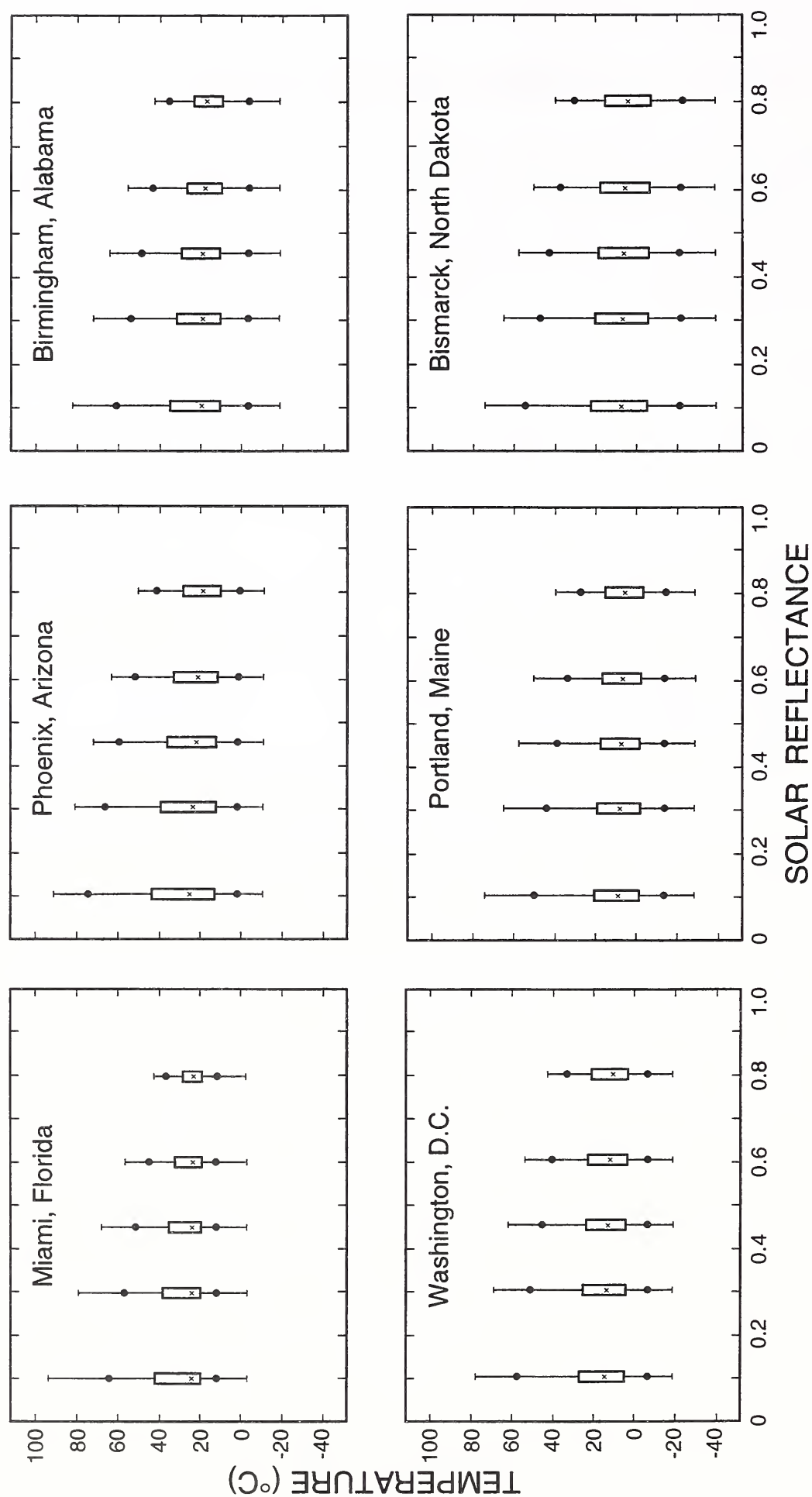


Figure 27

roof temperatures are below that data point and 5 % are above. The upper tic mark represents the peak roof temperatures.

As noted in Figure 27, only the roof temperatures above the median decreased as the solar reflectance increased from 0.1 to 0.8 (Figure 27). The implication is that the higher temperatures occurred during sunlight hours and, parenthetically, the low temperatures were during night and unaffected by changes in roof solar reflectance. At the estimated 95 % point and above, the decrease was substantial. For example, at Miami, the estimated 95 % point decreased from approximately 64 °C at $\rho = 0.1$ to 37 °C at $\rho = 0.8$ for a decrease of 27 K (49 °F). The estimated 95 % point temperatures for other locations are summarized in Table 14.

Table 14 Estimated 95 % Predicted Exterior Roof Temperatures										
Geographic Location	Roof Solar Reflectance									
	0.1		0.3		0.45		0.6		0.8	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
1. Miami, FL	64	148	57	135	51	124	45	114	37	98
2. Phoenix, AZ	74	165	66	150	59	138	52	125	42	107
3. Birmingham, AL	61	142	54	130	49	120	43	109	35	95
4. Washington, DC	58	137	51	125	46	115	41	105	33	91
5. Portland, ME	51	123	44	112	39	103	34	93	27	81
6. Bismarck, ND	54	129	48	118	42	108	37	99	30	86

Examination of the exterior temperature profiles provides further insight to the effect of the roof solar reflectance. Figure 28 illustrates the effect of solar reflectance on the daily temperature profile for a typical summer day (18 July) for each city. In each case, the temperature of the roof decreased substantially during sunlit hours as the solar reflectance increased. For Phoenix, the peak roof temperature (at hour 12) decreased about 40 K (72 °F) when ρ was increased from 0.1 to 0.8. (Note that the jagged changes in the profiles for Birmingham and Bismarck were due to the presence of cloud cover.) Figure 29 illustrates the seasonal effect of solar reflectance on the monthly average roof temperatures for the one-year simulation of weather data. In general, the exterior roof temperatures increased during spring and summer, and decreased during the autumn and winter. The effect of the solar reflectance was generally greater in summer months, as would be expected.

Daily Roof Temperature Profile for 18 July

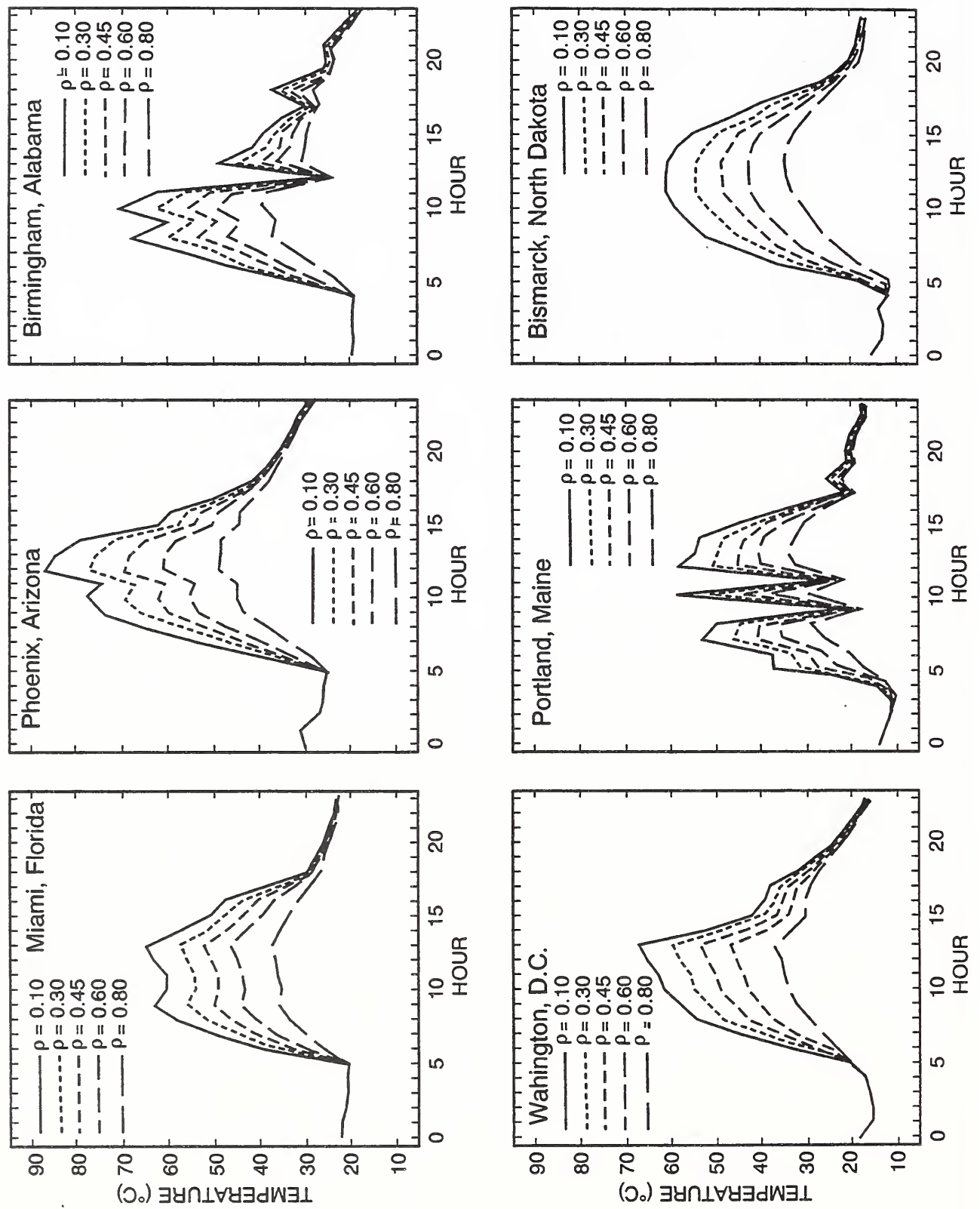


Figure 28

Average Monthly Roof Temperatures

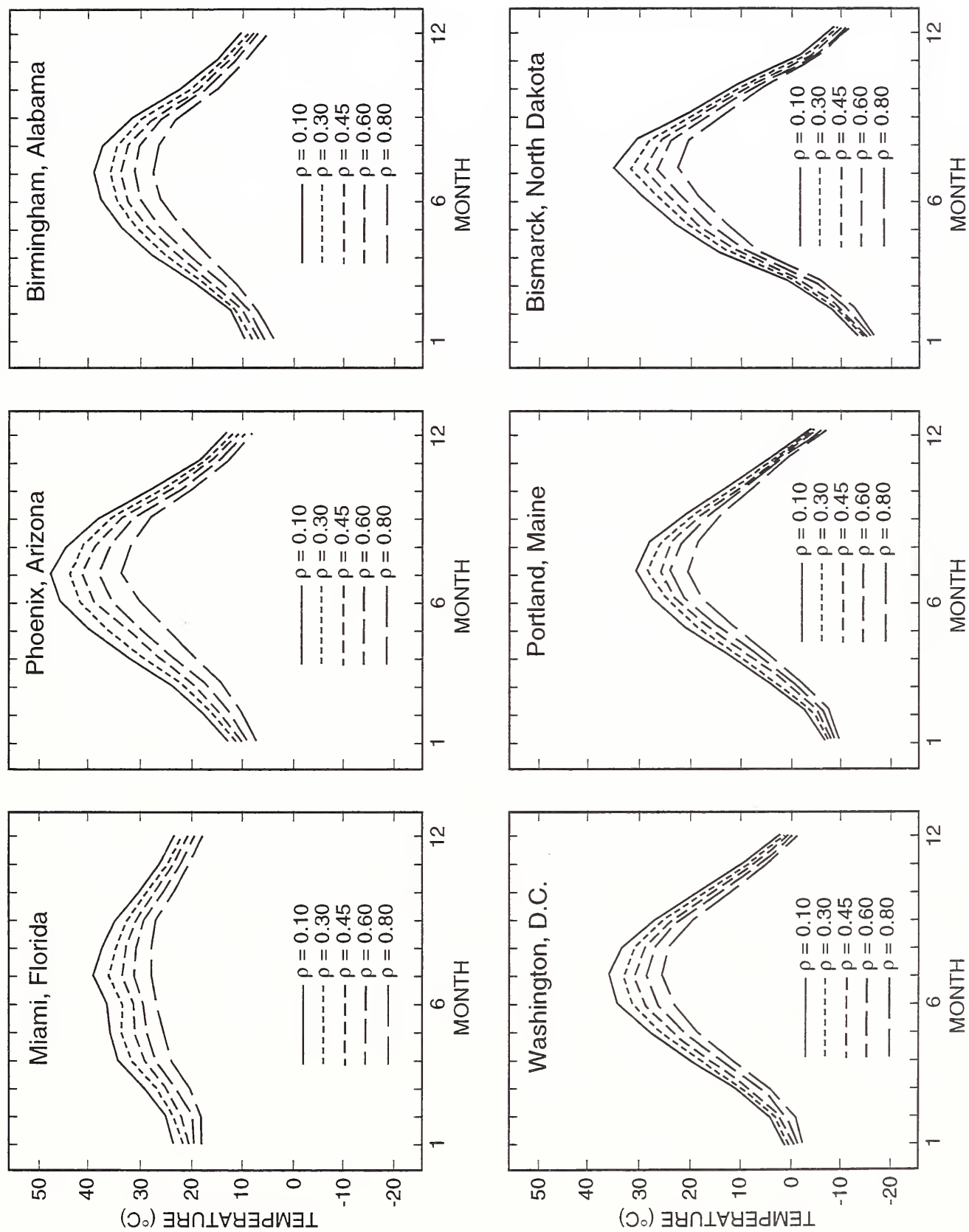


Figure 29

ECONOMIC DISCUSSION

Reflective roofs can provide a number of benefits. For utility companies, buildings with reflective roofs can help reduce the annual and peak cooling loads that the utilities must provide. For manufacturers of roofing materials, reflective roofs can reduce peak roof temperatures and thereby perhaps increase the service life of their product. For a homeowner, reflective roofs may in fact reduce the annual cost of cooling but may also increase the annual cost of heating. While a complete analysis of the advantages and disadvantages of solar reflective roofs is outside the scope of this report, a comparison of the annual energy costs can provide information about the conditions under which reflective roofs are cost effective to homeowners.

This section provides a simple comparative analysis of the annual energy costs for the ranch-style house with different levels of roof solar reflectance and ceiling insulation. The costs are computed for six different U.S. climates, using local residential utility rates and the TARP annual heating and cooling loads. Local residential utility rates for the summer of 1994 and winter 1994-1995 were obtained from the 17th nationwide survey of residential utility bills conducted by the National Association of Regulatory Utility Commissioners (NARUC 1995, 1996). Table 15 summarizes the average electric and gas rates for the six cities of interest for the summer of 1994 and winter 1994-1995.

Table 15 Average Local Utility (Electric and Gas) Rates Source: National Association of Regulatory Utility Commissioners			
City	Electric Summer 1994	Electric Winter 1994-1995	Gas Winter 1994-1995
	\$/kWh	\$/kWh	\$/Therm
1. Miami, FL	0.071	0.072	0.87
2. Phoenix, AZ	0.117	0.093	0.73
3. Birmingham, AL	0.075	0.072	0.59
4. Washington, DC	0.093	0.069	0.78
5. Portland, ME	0.121	0.130	0.70
6. Bismarck, ND	0.068	0.068	0.40

Recall that only annual (sensible) cooling loads for Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck have been presented previously. In order to determine the total (sensible and latent) cooling load for each location, latent cooling loads for Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck were determined by running additional TARP computer simulations. For these simulations, the relative humidities in the residences were limited to 60 % RH (ASHRAE Standard 90.2-1993). Because the latent load was essentially independent of the previously investigated parameters, only one run was conducted for each location. The solar

reflectance of the roof, the attic ventilation, and attic mass framing area were fixed at 0.45 (mid-level), 0.5 h^{-1} (lowest level), and 38.7 m^2 (mid-level), respectively. The residential building models utilized insulation levels set to their respective “base case” (Table 3). For these conditions, the annual latent cooling load for Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck were determined to be approximately 11,700 MJ, 560 MJ, 4,400 MJ, 3,100 MJ, 970 MJ, and 160 MJ, respectively. The total (sensible and latent) annual cooling loads were determined by combining the annual sensible cooling loads (see Figures 13 to 18) and annual latent cooling loads for each location.

The annual energy costs for heating and cooling were computed by assuming performance efficiencies for electric and gas equipment. The annual heating load was considered to be entirely satisfied by either electric resistance HVAC equipment or a gas furnace. The (local) performance efficiency of the electric equipment was assumed to be unity (1.0). The minimum requirement for the “annual fuel utilization efficiency” (AFUE) of the gas furnace was taken as 78 %, based on specifications in ASHRAE Standard 90.2-1993. For the cooling equipment, a “seasonal energy efficiency ratio” SEER of 10 was assumed (ASHRAE Standard 90.2-1993). The author acknowledges that the COP_c varies with location (due to outdoor temperature) and application, but for simplicity only a single value was used for the economic analysis. Recall, also that the air distribution system was assumed to be located within the conditioned space and, therefore, any thermal losses were neglected.

The annual energy costs for heating and cooling for Miami, Phoenix, Birmingham, Washington, D.C., Portland ME, and Bismarck are illustrated graphically in Figures 30 to 35, respectively. Each figure plots annual energy cost in U.S. (1994-1995) Dollars (\$) on the y-axis and solar reflectance of the roof on the x-axis for different levels of ceiling thermal resistance. These figures provide a relatively quick assessment whether the reflective roof can reduce annual energy costs for a given location. In general, if the slopes of the curves are negative (i.e., slope down with increasing solar reflectance), then a reflective roof reduces costs. Indeed, the greater the slope, the higher the potential savings. If the slopes of the lines are either horizontal (zero slope) or positive, then the effect is either inconsequential or detrimental (i.e., heating penalty results in higher cost), respectively.

As noted in Figures 30 and 31 for Miami and Phoenix, respectively, increasing the solar reflectance of the roof reduced the annual heating and cooling costs regardless of energy source and, in particular, for the case when the attic is uninsulated (i.e., “none”). In fact, for the uninsulated case, the annual heating and cooling savings for Miami and Phoenix were substantial, on the order of \$100, or more by increasing the solar reflectance from 0.1 to 0.8. For the other locations, the reduction in annual energy costs depended on the cost of heating energy, particularly for the heating dominated climates of Portland ME and Bismarck. For Portland ME and Bismarck, the effect was mostly inconsequential (i.e., very small effect) regardless of type of heating. In intermediate cooling climates such as Birmingham or Washington D.C., however, the effect depended on the type of heating. For gas heating, increasing the solar reflectance of the roof for an uninsulated attic reduced the annual heating

Annual Heating & Cooling - Miami, Florida

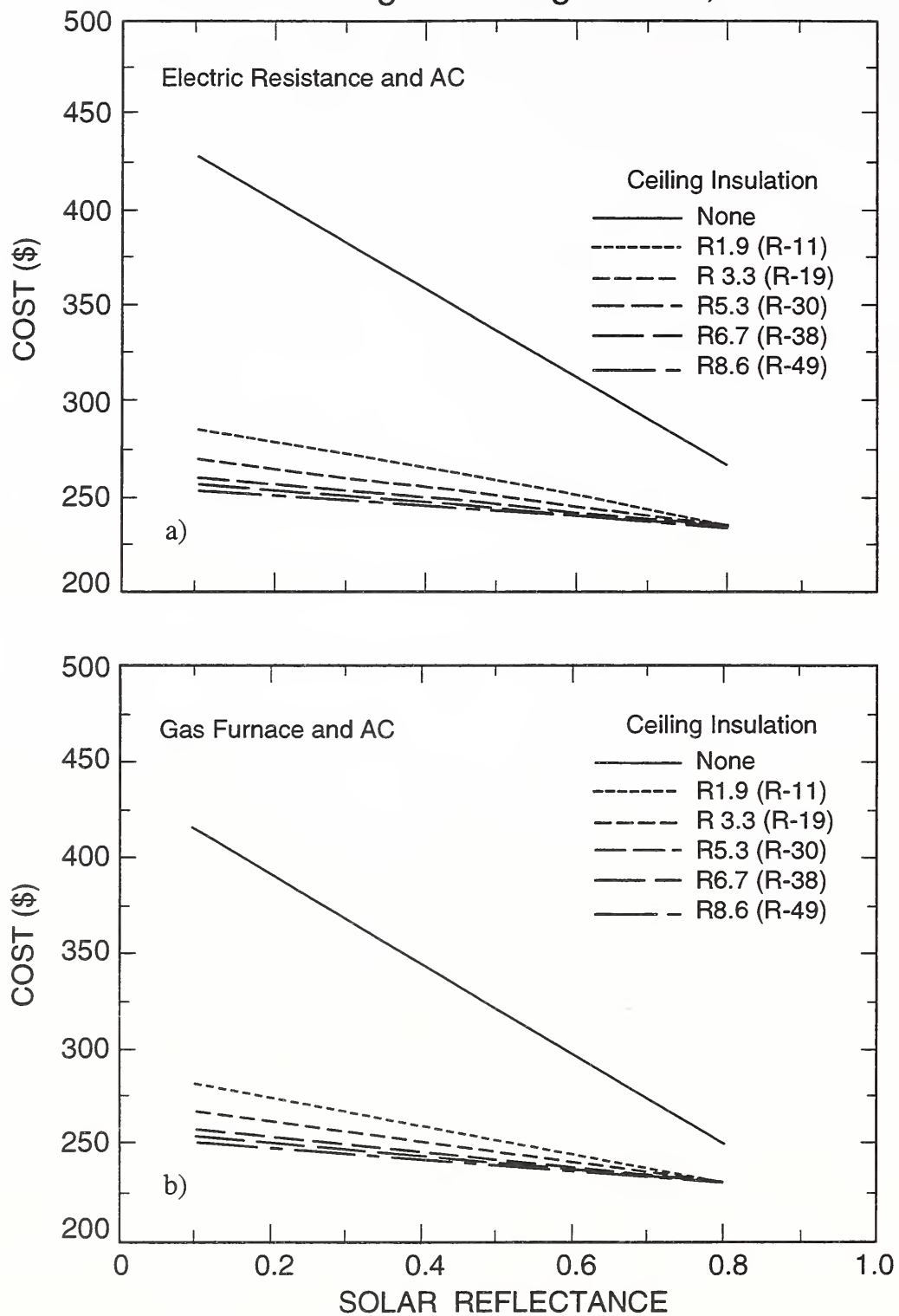


Figure 30

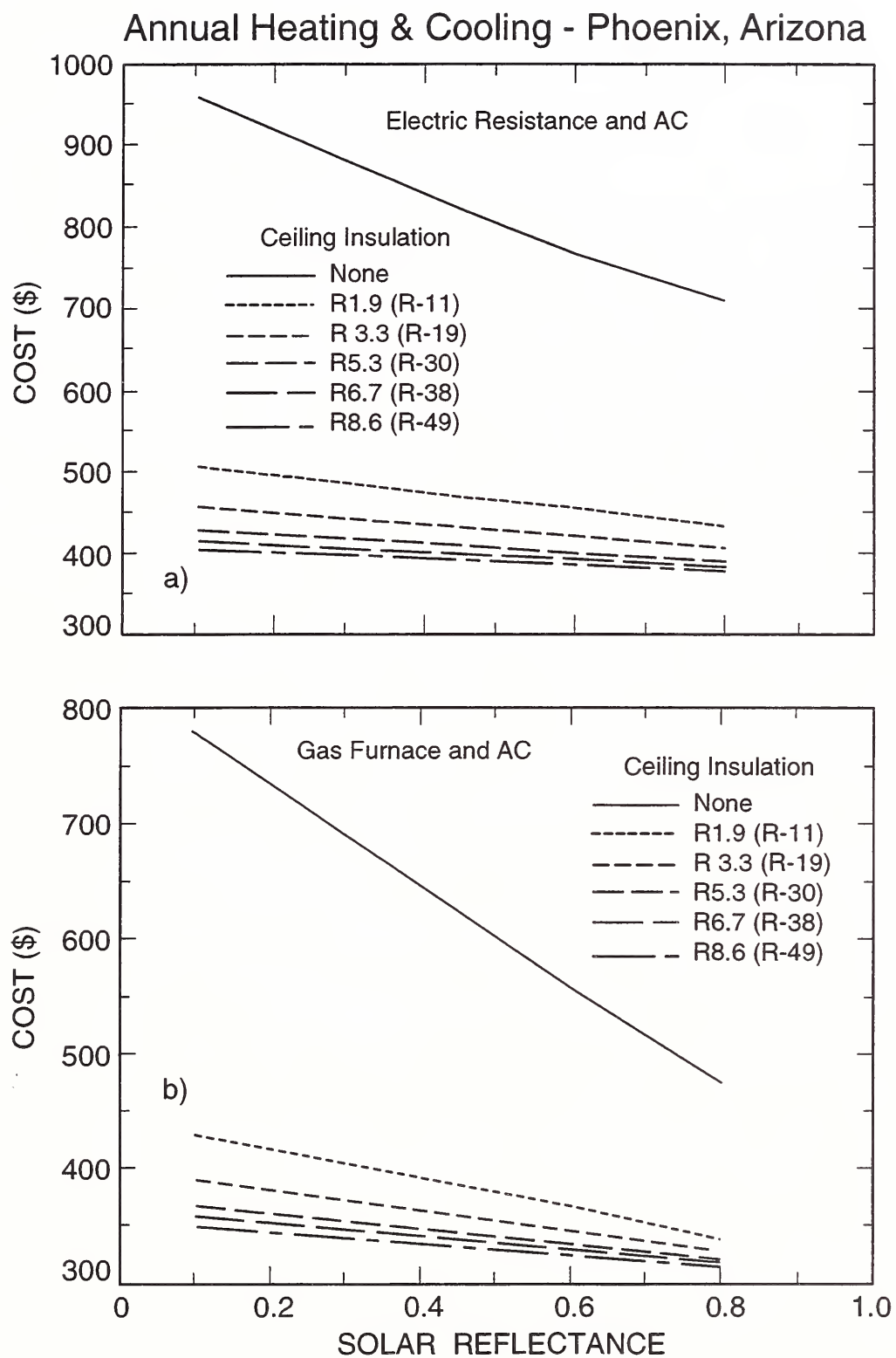


Figure 31

Annual Heating & Cooling - Birmingham, Alabama

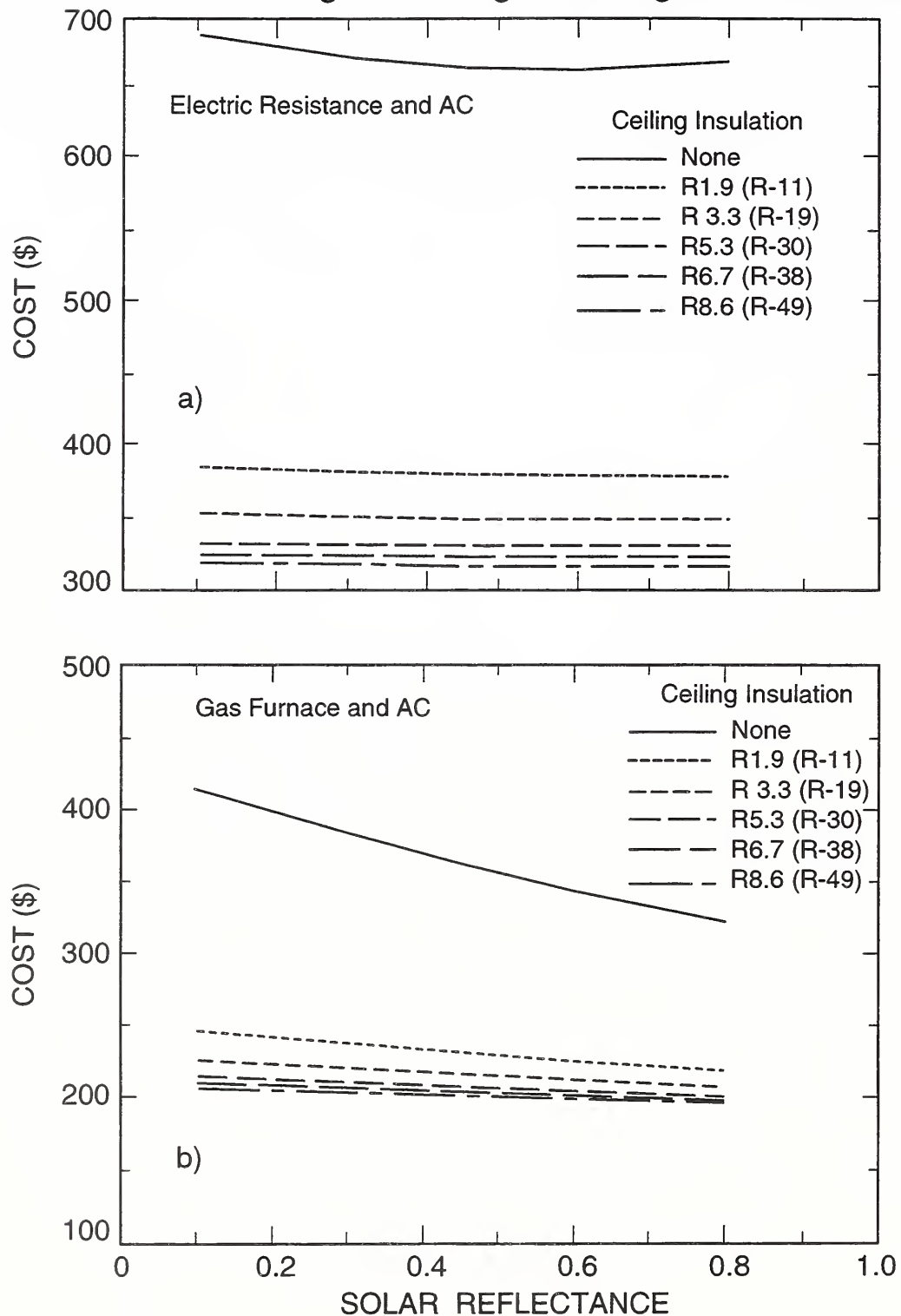


Figure 32

Annual Heating & Cooling - Washington, D.C.

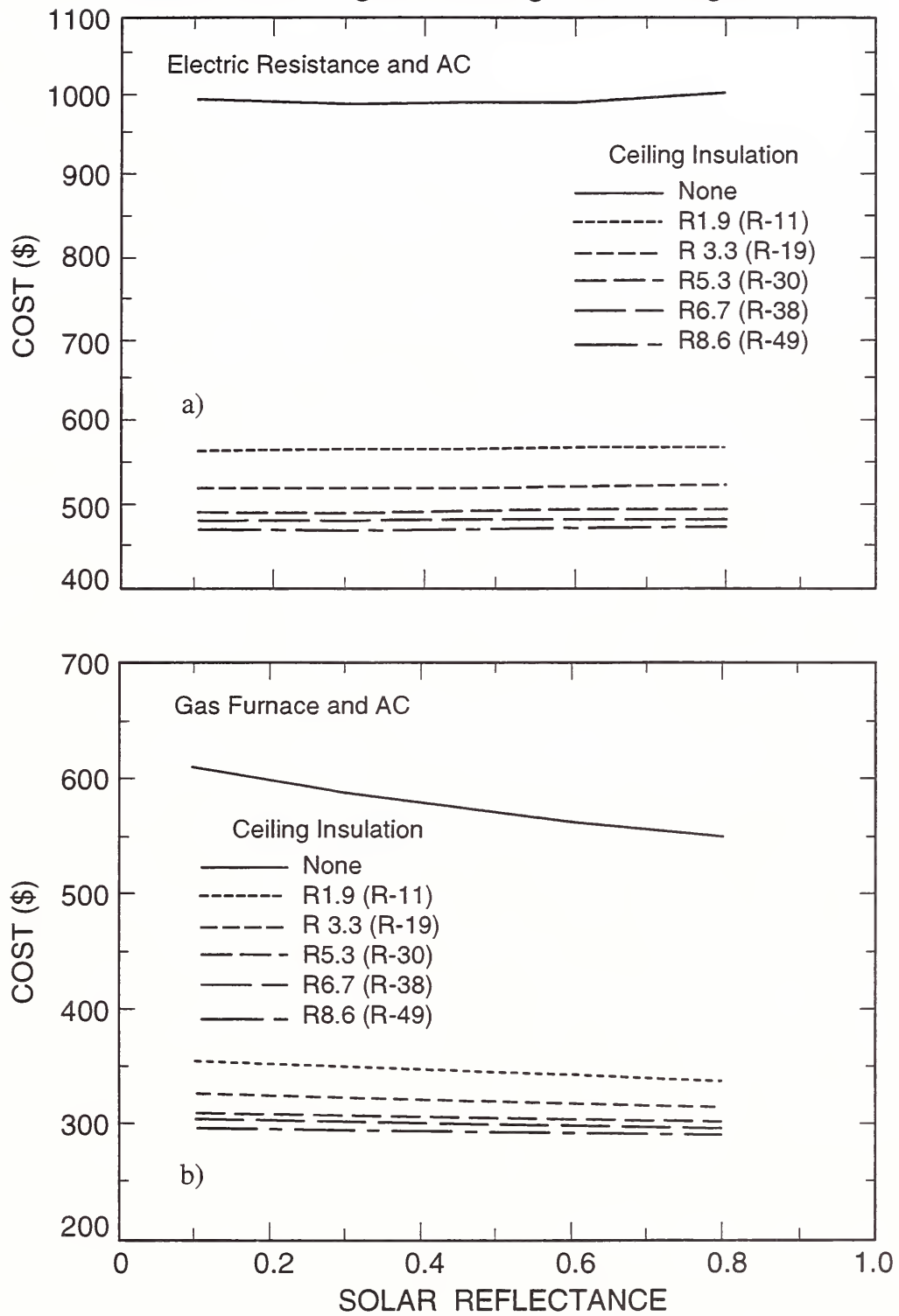


Figure 33

Annual Heating & Cooling - Portland, Maine

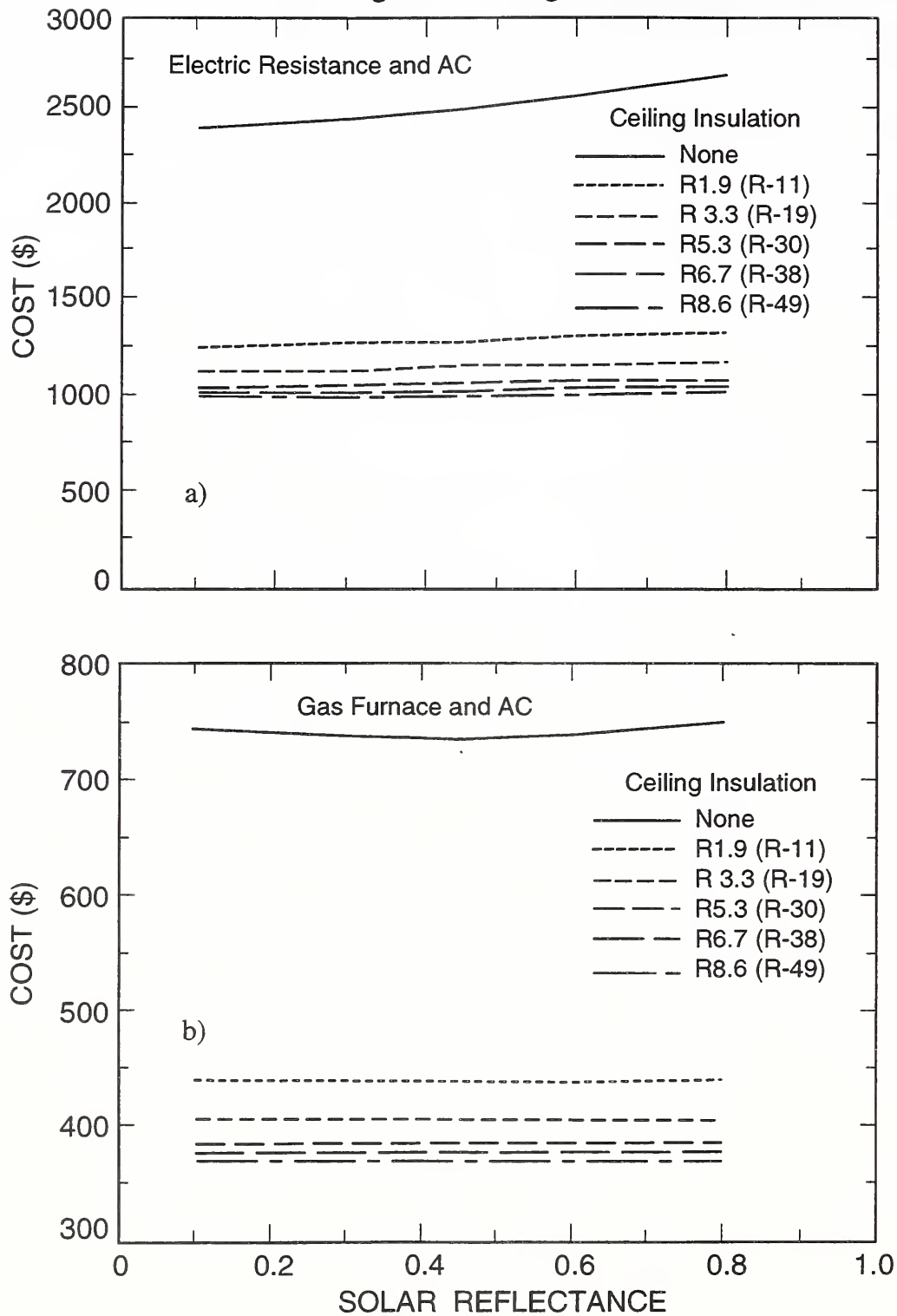


Figure 34

Annual Heating & Cooling - Bismarck, North Dakota

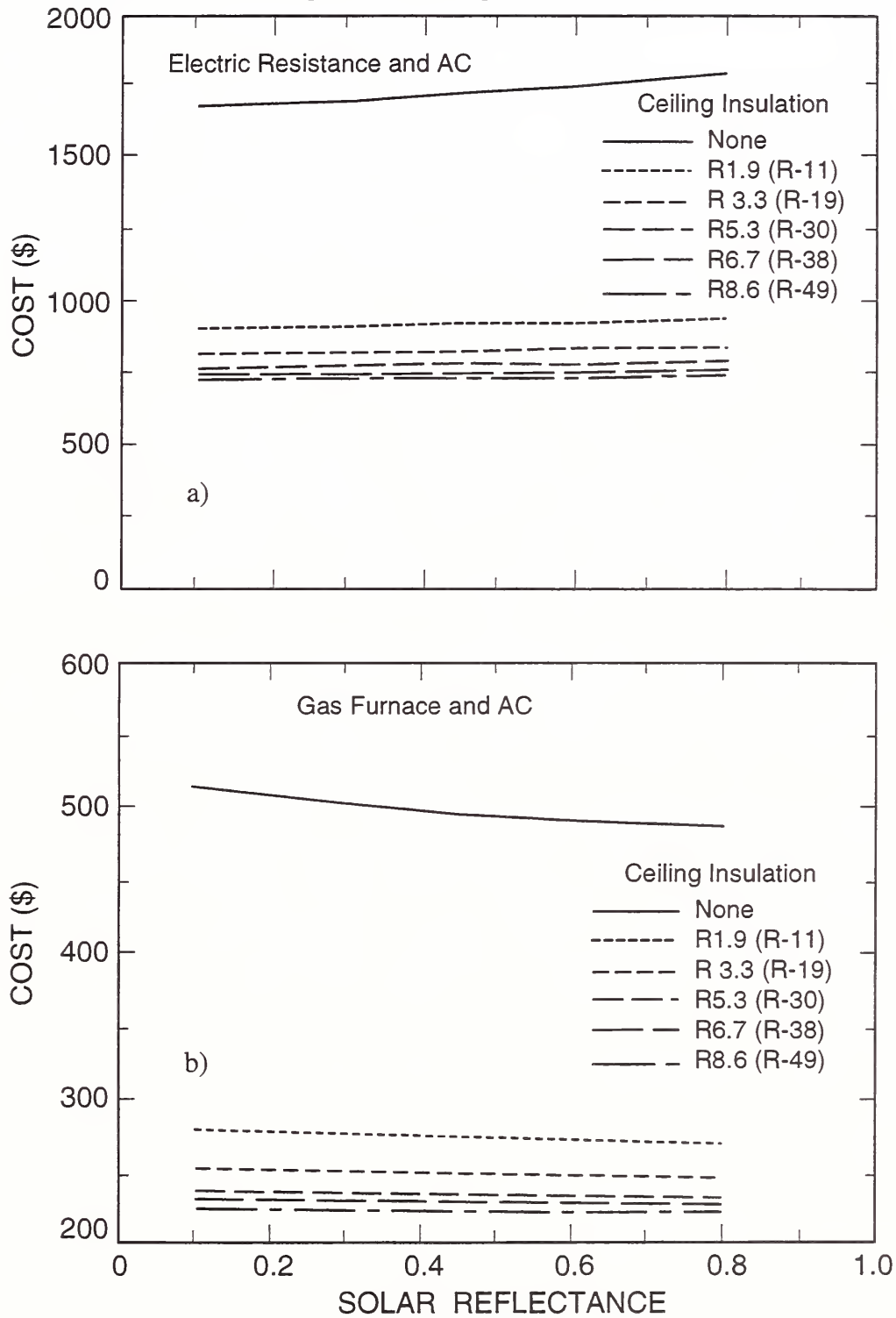


Figure 35

and cooling costs for Birmingham and, to a lesser extent, for Washington D.C. It is important to note, however, that for the well-insulated residences (i.e., base case ceiling levels of thermal insulation), the annual energy savings were less.

At least three important factors qualify the analysis. First, Figures 30 through 35 do not include the initial costs of a reflective roof; these costs may vary significantly. A more complete analysis which includes initial costs is necessary to determine whether reflective roofs are indeed *life-cycle* cost effective to homeowners. Second, it is yet to be determined whether reflective roofs can, in practice, sustain the higher levels of solar reflectance ($\rho \geq 0.7$) shown in the figures. Roofs with this level of reflectivity may be cost effective but additional factors may have to be considered such as periodic cleaning, re-coating, etc. Finally, the analysis is valid only for the models examined. The results may not apply to other building geometries or geographical locations outside the conditions shown in Figure 1 or 2.

SUMMARY AND CONCLUSIONS

Annual heating (cooling) loads, peak heating (cooling) loads, and exterior roof temperatures have been computed for a small one-story “ranch style” house using the Thermal Analysis Research Program (TARP). Thermal performance requirements for the house were based, in part, on the prescriptive criteria established in ASHRAE Standard 90.2-1993 (ASHRAE 1993). The model, with minor modifications in the thermal envelope for different geographic locations, was subjected to hourly weather data compiled in the Weather Year for Energy Calculations (Crow 1981) for locations: Birmingham, Alabama; Bismarck, North Dakota; Miami, Florida; Phoenix, Arizona; Portland, Maine; and, Washington D.C. These geographic locations were specifically selected to examine the extreme and mid-climatic conditions in the contiguous United States.

Building Loads

The results of the building load analysis can be summarized as follows.

- *Geographic Location:* Of the five factors studied - roof solar reflectance, geographic location, ceiling thermal resistance, attic ventilation, and attic mass framing area - geographic location had the greatest global effect on annual heating (cooling) and peak heating. Increasing the ceiling thermal resistance from none to $R-8.6 \text{ m}^2 \cdot \text{K/W}$ ($R-49 \text{ h} \cdot \text{ft}^2 \cdot ^\circ\text{F/Btu}$) had the greatest global effect on peak cooling.
- *Ceiling Thermal Resistance:* In almost all geographic locations, the effect of increasing the ceiling thermal resistance was beneficial. That is, for higher levels of thermal insulation, both the annual and peak heating (cooling) loads were reduced, although, in general, the effects diminished as the levels of ceiling thermal resistance increased.
- *Roof Solar Reflectance:* In all geographic locations, the effect of increasing the roof solar reflectance 1) reduced annual and peak cooling loads, 2) was insignificant for peak heating loads, and 3) detrimental (meaning increased requirements) for annual heating loads. Further, the lowest annual cooling load was obtained at the highest level of roof solar reflectance. An analysis of the subset of the annual and peak heating (cooling) data for each geographic location indicated the following:
 - ▶ The effect of increasing the roof solar reflectance appeared to result in a linear decrease in cooling load requirements.
 - ▶ The greatest effect of increasing the roof solar reflectance was for the case of an uninsulated attic. For higher levels of ceiling thermal resistance, increasing the roof solar reflectance reduced the annual and peak cooling loads, but to a lesser extent.
- *Attic Ventilation:* In all geographic locations, the effect of increasing the attic ventilation provided beneficial results for annual and peak cooling loads and detrimental results (meaning increased requirements) for annual and peak heating loads. It is important to note, however, that other

considerations such as moisture control should be considered in determining the proper ventilation rates for an attic.

- *Attic Mass Framing Area:* In all geographic locations, the effect of the attic mass framing area was inconsequential.
- *Constant Ambient Conditions Analysis:* An extended analysis of building loads was conducted using the building model at an arbitrary site subjected to a transient solar profile and steady ambient conditions of either $-1.1\text{ }^{\circ}\text{C}$ ($30\text{ }^{\circ}\text{F}$) for heating or $26.7\text{ }^{\circ}\text{C}$ ($80\text{ }^{\circ}\text{F}$) for cooling.
 - The behavior of the predicted heating and cooling loads under steady ambient conditions was similar to the annual loads computed for hourly weather data.
 - Radiative cooling of the structure at night significantly affected the cooling load and was particularly noticeable at high values of roof solar reflectance. The presence of thermal insulation in the ceiling reduced the effect of night-time radiative cooling.

Exterior Roof Temperatures

The results of the exterior roof temperature analysis for one year of weather data are summarized as follows.

- *Statistical Summary:* The exterior surface roof temperatures above the median value decreased when the roof solar reflectance was increased. Surface temperatures at the 95 % level and above were reduced substantially.
- *Daily and Average Monthly Profiles:* These profiles verified that the peak exterior roof temperatures were reduced substantially by increasing the roof solar reflectance.

Economic Analysis

The results of the economic cost analysis are summarized as follows.

- *Miami and Phoenix (Hot Climates):* Substantial annual cost savings were realized for the case of an uninsulated attic for both gas or electric heating. For higher levels of ceiling thermal resistance, smaller annual cost savings were also evident.
- *Birmingham and Washington D.C. (Intermediate Climates):* Annual cost savings for Birmingham and, to a lesser extent Washington D.C., were realized for the case of an uninsulated attic and for gas heating.
- *Portland ME and Bismarck (Cold Climates):* Annual cost savings were generally small in all cases.

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APPENDIX A

Environment input data prepared for Miami, Florida. Note, the dollar (\$) symbol specifies a comment for TARP.

```
$ EF1 Environment Input File - use in conjunction with BD1
$ Project: Assessment of Reflective Roof Coatings
$ Location: Miami, Florida
$
$ Ground temperatures were taken from Appendix A, NBSIR 81-2378, "Heat
$ Transfer Analysis of Underground Heat and Chilled-Water Distribution
$ Systems". Geographic data was taken from the 1993 ASHRAE Fundamentals
$ Handbook, Chapter 24. Weather data were taken from ASRHRAE Weather
$ Year for Energy Calculations (WYEC). Site number identifies the weather
$ recording site.
$
RC(DEM/UIN=ENGLISH/UOUT=ENGLISH)
LOC(DESC='MIAMI, FLORIDA'/LATD=25.8/LONG=80.3/TZ=5/ALT=7)
GRND(GRT=12*75.0)
WTAP(DESC='WYEC DATA FOR MIAMI'/TYPE=WYEC/SITE=12839)
$
```

APPENDIX B

Building Description Input File prepared for Miami, Florida. Note, the dollar (\$) symbol specifies a comment for TARP.

```
$ BD1
$ Building Description Input File - use in conjunction with EF1
$ Project: Assessment of Reflective Roof Coatings
$ Location: Miami, Florida
$
$ Data will be converted from English units input to Metric for the simulation and reports.
$
PROJECT [
  RC(DEM/UIIN=ENGLISH/UOUT=METRIC/DESC='ASSESSMENT OF REFLECTIVE ROOF COATINGS')
  RPT(DAILY/WIDTH=80)
]
$
$ Heating and cooling day schedules are specified according to ASHRAE Standard 90.2-1993: 20°C (68°F) for
$ heating with night setback of 15.6°C (60°F); and 26°C (78°F) for cooling. Daily internal gains for occupancy,
$ lighting, and equipment were based on the profile provided in ASHRAE Standard 90.2-1993, Table 8-1.
$ Infiltration air day schedules were assumed constant. The building envelope above grade is wood-frame
$ construction with a crawl space foundation. Thermal transmission properties for materials are taken from
$ the 1993 ASHRAE Fundamentals Handbook. Solar absorptance for exterior surfaces is 0.5, per 90.2-1992,
$ except roof asphalt shingles. The solar absorptance ( $\alpha=A$ ) of the roof asphalt shingles varies from A=0.90
$ non-reflective, to A=0.80, reflective. Infrared emittance,  $\epsilon=0.9$ .
$
LIBRARY [
$ LIB(ALL) $ Remove comment for detailed library reports.
DS(NAME=H1/DESC='ZONE2 HEATING SETBK'/T=6*60.0,17*68.0,1*60.0)
DS(NAME=C1/DESC='ZONE2 COOLING TEMPS'/T=24*78.0)
DS(NAME=OC/DESC='ZONE2 OCCUPANCY'/FFC=0.5,4*0.45,0.55,3*0.8,2*0.95,8*0.8,
3*0.7,0.6,0.5)
DS(NAME=LT/DESC='ZONE2 LIGHTING'/FFC=5*0.05,0.1,0.25,0.5,0.4,0.2,6*0.0,0.3,
2*0.55,0.5,2*0.45,0.35,0.1)
DS(NAME=EQ/DESC='ZONE2 EQUIPMENT'/FFC=0.19,0.17,3*0.16,2*0.17,0.33,0.35,
0.51,0.65,0.48,0.47,0.23,0.20,0.24,0.45,2*0.38,2*0.25,0.33,0.26,0.19)
DS(NAME=IN/DESC='INFILTRATION'/FFC=24*1.0)
WS(NAME=HEAT/DESC='HEATING'/ALL=H1)
WS(NAME=COOL/DESC='COOLING'/ALL=C1)
WS(NAME=OCU/DESC='OCCUPANCY'/ALL=OC)
WS(NAME=LAMP/DESC='LIGHTING '/ALL=LT)
WS(NAME=EQPT/DESC='EQUIPMENT'/ALL=EQ)
WS(NAME=INFL/DESC='INFILTRATION'/ALL=IN)
MATL(NAME=AOR/DESC='AIR SPACE RESISTANCE'/R=0.91/AIR)
MATL(NAME=ASP/DESC='ASPHALT ROOF SHINGLE'/K=0.0236/D=70.0/CP=0.30/A=0.25/E=0.9)
MATL(NAME=CRP/DESC='CARPET & PAD'/R=1.23)
MATL(NAME=CMU8/DESC='8 CMU, OPEN CORE'/K=0.654/D=136.0/CP=0.22/A=0.5/E=0.9)
MATL(NAME=FLT/DESC='FELT BUILDING MEMBRANE'/R=0.06)
MATL(NAME=FSH/DESC='FIBERBOARD SHEATHING'/K=0.0317/D=18.0/CP=0.31)
MATL(NAME=R19/DESC='FGL R19 INSULATION'/R=19.0)
MATL(NAME=R30/DESC='FGL R30 INSULATION'/R=30.0)
MATL(NAME=R38/DESC='FGL R38 INSULATION'/R=38.0)
MATL(NAME=R49/DESC='FGL R49 INSULATION'/R=49.0)
MATL(NAME=R11/DESC='FGL R11 WALL INSULATION'/R=11.0)
MATL(NAME=R13/DESC='FGL R13 WALL INSULATION'/R=13.0)
MATL(NAME=R15/DESC='FGL R15 WALL INSULATION'/R=15.0)
MATL(NAME=GLS/DESC='GLAZING, SINGLE 1/8 PANE'/GLASS/R=0.28/SC=0.5)
MATL(NAME=GLD/DESC='GLAZING, DOUBLE 1/8 PANE'/GLASS/R=1.98/SC=0.7)
MATL(NAME=GYP/DESC='GYPSUM WALLBOARD'/K=0.0925/D=50.0/CP=0.26)
MATL(NAME=PLY/DESC='PLYWOOD FIR SHEATHING'/K=0.0672/D=34.0/CP=0.29)
```

```

MATL(NAME=XPS/DESC='POLYSTYRENE SHEATHING'/K=0.0167/D=2.7/CP=0.29)
MATL(NAME=WOD/DESC='SOFTWOOD FRAMING'/K=0.0667/D=38.0/CP=0.39)
MATL(NAME=DRT/DESC='SOIL, TYPICAL'/K=0.8/D=120.0/CP=0.2/A=0.7)
MATL(NAME=SND/DESC='STONE, LIME, SAND FILL'/K=2.0/D=140.0/CP=0.2)
MATL(NAME=WSD/DESC='WOOD SIDING, LAPPED'/K=0.0513/D=27.0/CP=0.28/A=0.5/E=0.9)
MATL(NAME=DOR/DESC='WOOD DOOR, SOLID CORE'/R=1.65/A=0.5/E=0.9)
CONS(NAME=WALL1A/DESC='EXTERIOR FRAME WALL, CAVITY INSULATION'/
  MATL=0.0417,WSD,0.0833,XPS,0.0,R15,0.0417,GYP/ORGH=6)
CONS(NAME=WALL1B/DESC='EXTERIOR FRAME WALL, 2 by 4 STUD'/
  MATL=0.0417,WSD,0.0833,XPS,0.292,WOD,0.0417,GYP/ORGH=6)
CONS(NAME=WALL2/DESC='CRAWL SPACE WALL'/
  MATL=0.6354,CMU8/ORGH=2)
CONS(NAME=WALL3A/DESC='ATTIC GABLE WALL, CAVITY'/
  MATL=0.0417,WSD,0.0417,FSH/ORGH=6)
CONS(NAME=WALL3B/DESC='ATTIC GABLE WALL, 2 by 4 STUD'/
  MATL=0.0417,WSD,0.0417,FSH,0.292,WOD/ORGH=6)
CONS(NAME=CEIL1A/DESC='ATTIC FLOOR ZONE1, CAVITY INSULATION'/
  MATL=0.0417,GYP,0.0,R38)
CONS(NAME=CEIL1B/DESC='ATTIC FLOOR ZONE1, 2 by 4 TRUSS JOIST'/
  MATL=0.0417,GYP,0.292,WOD)
CONS(NAME=CEIL2A/DESC='CEILING ZONE2, CAVITY INSULATION'/
  MATL=0.0,R38,0.0417,GYP)
CONS(NAME=CEIL2B/DESC='CEILING ZONE2, 2 by 4 TRUSS JOIST'/
  MATL=0.292,WOD,0.0417,GYP)
CONS(NAME=ROOF1A/DESC='ASPHALT SHINGLE ROOF, CAVITY'/
  MATL=0.0208,ASP,0,FLT,0.0521,PLY/ORGH=3)
CONS(NAME=ROOF1B/DESC='ASPHALT SHINGLE ROOF, 2 by 4 RAFTER'/
  MATL=0.0208,ASP,0,FLT,0.0521,PLY,0.292,WOD/ORGH=3)
CONS(NAME=FLOOR2A/DESC='FRAME FLOOR ZONE2, CAVITY INSULATION'/
  MATL=0.0,R19,0.0521,PLY,0,CRP)
CONS(NAME=FLOOR2B/DESC='FRAME FLOOR ZONE2, 2 by 10 FLOOR JOIST'/
  MATL=0.792,WOD,0.0521,PLY,0,CRP)
CONS(NAME=FLOOR3A/DESC='FRAME FLOOR ZONE3, CAVITY INSULATION'/
  MATL=0,CRP,0.0521,PLY,0.0,R19)
CONS(NAME=FLOOR3B/DESC='FRAME FLOOR ZONE3, 2 by 10 FLOOR JOIST'/
  MATL=0,CRP,0.0521,PLY,0.792,WOD)
CONS(NAME=PART/DESC='PARTITION WALL'/MATL=0.0417,GYP,0.0,AOR,0.0417,GYP)
CONS(NAME=DOOR/DESC='SOLID WOOD DOOR'/MATL=0.0,DOR)
CONS(NAME=TRUSS/DESC='ATTIC WOOD TRUSS'/MATL=0.125,WOD/ORGH=4)
CONS(NAME=CRSPFL/DESC='CRAWL SPACE FLOOR'/MATL=1.0,DRT,0.333,SND)
CONS(NAME=WINDOW/DESC='SINGLE PANE GLAZING'/MATL=0.0,GLS/ORGH=6)
]
$
$ The house is divided into three zones. Zone 1 is a vented attic; Zone 2, a conditioned living space;
$ and Zone 3, a vented crawl space. Report variables, when needed, are ambient air (average) and building
$ consumption values. Simulation parameters are as follows: 1) default values for convergence criteria for
$ temperature (0.05K, 0.01°F), heating and cooling loads (0.01 W), minimum load, and maximum number of
$ iterations; 2) simple air flow algorithm (Flow = 0, default); 3) shading from 'SHD' surfaces only;
$ 4) heat balance method computed at the beginning of each time step; 5) detailed MRT network algorithm;
$ and, 6) detailed algorithms for exterior and interior surface coefficients.
$
BUILDING [
SIM(ZON=ZONE1,ZONE2,ZONE3/SYS=LOADS/
CNVG=0.09,0.01,0.34,6/SLDS=0/HTB=0/RIM=2/HO=2/HI=2)
]
$
$ ZONE1 - attic. The volume of the attic is calculated on a net basis by subtracting the truss volume (22
$ members). Infiltration rates are taken from, "Survey of Moisture Levels In Attics" by Buchan, Lawton, &
$ Parent, Ltd and ranged from 0.5 to 10 air changes per hour. The surface mass is based on 22 trusses.
$ Framing percentages for 600 mm (24") O.C. trusses are 7 percent (93 percent cavity). Gable wall framing
$ percentages are 15 percent (85 percent cavity). The framing in the gable walls is handled as a
$ subsurface. Parallel paths for heat flow are assumed for the frame construction. The ceiling is defined

```


\$ as an interzonal partition.

\$

ZONE [

GEOM(NAME=ZONE1/VOL=4088.38)

INF(WS=INFL/CAP=31.5/C=1.0/T=0.0/V=0.0)

MASS(CONS=TRUSS/AREA=417.08)

SRF(EX/OP/BS/CONS=ROOF1A/AZM=0.0/TILT=22.620/SIZE=39.06,16.611)

SRF(EX/OP/BS/CONS=ROOF1B/AZM=0.0/TILT=22.620/SIZE=2.94,16.611)

SRF(EX/OP/BS/CONS=ROOF1A/AZM=180.0/TILT=22.620/SIZE=39.06,16.611)

SRF(EX/OP/BS/CONS=ROOF1B/AZM=180.0/TILT=22.620/SIZE=2.94,16.611)

SRF(IN/OP/BS/CONS=CEIL1A/AZM=180.0/TILT=180.0/SIZE=39.06,28.0/ZONE=ZONE2)

SRF(IN/OP/BS/CONS=CEIL1B/AZM=180.0/TILT=180.0/SIZE=2.94,28.0/ZONE=ZONE2)

SRF(EX/OP/BS/CONS=CEIL1A/AZM=180.0/TILT=180.0/SIZE=39.06,2.667)

SRF(EX/OP/BS/CONS=CEIL1B/AZM=180.0/TILT=180.0/SIZE=2.94,2.667)

SRF(EX/OP/BS/CONS=WALL3A/AZM=90.0/TILT=90.0/VRTS=30.667,0.0,15.333,6.389)

SRF(EX/OP/SS/CONS=WALL3B/SIZE=9.0,1.6327/ORG=10.8333,0.0,0.0)

SRF(EX/OP/BS/CONS=WALL3A/AZM=270.0/TILT=90.0/VRTS=30.667,0.0,15.333,6.389)

SRF(EX/OP/SS/CONS=WALL3B/SIZE=9.0,1.6327/ORG=10.8333,0.0,0.0)

]

\$

\$ ZONE2 - conditioned space. The volume of the living space is calculated on a gross basis. No adjustments are made for the volume of the interior furnishings or partitions. Two adults inhabit the house (all times).

\$ Lighting is incandescent, 600 W. Major equipment totals 820 W (2.8 kBtuh), all electric. The infiltration rate is 0.5 ACH (ASHRAE 90.2-1993). Mass is estimated from area of internal partition walls. Framing percentages for 400 mm (16") O.C. studs are 25 percent (75 percent cavity); for 400 mm (16") O.C. floor joists, 10 percent (90 percent cavity). Parallel paths for heat flow are computed for frame construction.

\$ The ceiling and floor are defined as an interzonal partition. The roof overhangs the front (South) and rear (North) elevations by 400 mm (16 in.). Window area combined on front and rear (includes glass door)

\$ elevations. Windows and door are setback 25 mm (1 in.) in the wall.

\$

ZONE [

GEOM(NAME=ZONE2/VOL=9408.0)

PEO(WS=OCCU/CAP=2.0)

LIT(WS=LAMP/CAP=2.0/RAD=0.8/VIS=0.1/REP=0.1)

EQP(WS=EQPT/CAP=2.8/EL)

INF(WS=INFL/CAP=78.4/C=1.0/T=0.0/V=0.0)

MASS(CONS=PART/AREA=880)

SRF(IN/OP/BS/CONS=CEIL2A/AZM=180.0/TILT=0.0/SIZE=39.06,28.0/ZONE=ZONE1)

SRF(IN/OP/BS/CONS=CEIL2B/AZM=180.0/TILT=0.0/SIZE=2.94,28.0/ZONE=ZONE1)

SRF(EX/OP/BS/CONS=WALL1A/AZM=0.0/TILT=90.0/SIZE=42.0,8.0)

SHD(OHNG/SIZE=42.0,1.333/ORG=0.0,8.0,0.0)

SRF(EX/TR/SS/CONS=WINDOW/SIZE=11.0,5.0/ORG=2.0,2.0,0.0/RVL=0.0833,0.0,0.0,0.0)

SRF(EX/OP/SS/CONS=DOOR/SIZE=3.0,6.667/ORG=15.0,0.0,0.0/RVL=0.0833,0.0,0.0,0.0)

SRF(EX/OP/SS/CONS=WALL1B/SIZE=8.156,8.0/ORG=33.844,0.0,0.0)

SRF(EX/OP/BS/CONS=WALL1A/AZM=90.0/TILT=90.0/SIZE=23.8,8.0)

SRF(EX/OP/BS/CONS=WALL1B/AZM=90.0/TILT=90.0/SIZE=4.2,8.0)

SRF(EX/OP/BS/CONS=WALL1A/AZM=180.0/TILT=90.0/SIZE=42.0,8.0)

SHD(OHNG/SIZE=42.0,1.333/ORG=0.0,8.0,0.0)

SRF(EX/TR/SS/CONS=WINDOW/SIZE=6.0,6.667/ORG=2.0,0.0,0.0/RVL=0.0833,0.0,0.0,0.0)

SRF(EX/TR/SS/CONS=WINDOW/SIZE=8.0,4.0/ORG=10.0,3.0,0.0/RVL=0.0833,0.0,0.0,0.0)

SRF(EX/OP/BS/CONS=WALL1B/SIZE=8.25,8.0/ORG=33.75,0.0,0.0)

SRF(EX/OP/BS/CONS=WALL1A/AZM=270.0/TILT=90.0/SIZE=21.0,8.0)

SRF(EX/OP/BS/CONS=WALL1B/AZM=270.0/TILT=90.0/SIZE=7.0,8.0)

SRF(IN/OP/BS/CONS=FLOOR2A/AZM=180.0/TILT=180.0/SIZE=37.8,28.0/ZONE=ZONE3)

SRF(IN/OP/BS/CONS=FLOOR2B/AZM=180.0/TILT=180.0/SIZE=4.2,28.0/ZONE=ZONE3)

]

\$

\$ ZONE3 - vented crawl space, 2 ft height. ACH = 1, based on paper by Samuelson, 1994.

\$

ZONE [

GEOM(NAME=ZONE3/VOL=2352.0)

INF(WS=INFL/CAP=39.2/C=1.0/T=0.0/V=0.0)

```

SRF(IN/OP/BS/CONS=FLOOR3A/AZM=180.0/TILT=0.0/SIZE=37.8,28.0/ZONE=ZONE2)
SRF(IN/OP/BS/CONS=FLOOR3B/AZM=180.0/TILT=0.0/SIZE=4.2,28.0/ZONE=ZONE2)
SRF(EX/OP/BS/CONS=WALL2/AZM=0.0/TILT=90.0/SIZE=42.0,2.0)
SRF(EX/OP/BS/CONS=WALL2/AZM=90.0/TILT=90.0/SIZE=28.0,2.0)
SRF(EX/OP/BS/CONS=WALL2/AZM=180.0/TILT=90.0/SIZE=42.0,2.0)
SRF(EX/OP/BS/CONS=WALL2/AZM=270.0/TILT=90.0/SIZE=28.0,2.0)
SRF(EX/OP/BS/CONS=CRSPFL/AZM=180.0/TILT=180.0/SIZE=42.0,28.0)
]
$
SYSTEM [
  SYS(NAME=LOADS)
  UNC(ZONE=ZONE1)
  DES(ZONE=ZONE2/HTWS=HEAT/CLWS=COOL)
  UNC(ZONE=ZONE3)
]

```

APPENDIX C

Environment input data prepared for "design day" heating and cooling, arbitrary location. Note, the dollar (\$) symbol specifies a comment for TARP.

```
$ EFDH1 Environment Input File - use in conjunction with BDD1
$ Project: Assessment of Reflective Roof Coatings
$ Location: Time Zone Meridian in U.S. (Springfield, IL)
$
$ Ground temperatures were taken from Appendix A, NBSIR 81-2378, "Heat
$ Transfer Analysis of Underground Heat and Chilled-Water Distribution
$ Systems".

$ 1-Day design data - HEATING.
$
RC(DEM/UIN=ENGLISH/UOUT=ENGLISH)
LOC(DESC='TIME ZONE MERIDIAN LONG 90, LAT 40'/LATD=40/LONG=90/TZ=6/ALT=587)
GRND(GRT=12*52.0)
DAY(DESC='24 TEMPERATURES'/DATE=21SEPT/CLR=1/CLD=24*0/TA=24*30)
$
```

```
$ EFDC1 Environment Input File - use in conjunction with BDD1
$ Project: Assessment of Reflective Roof Coatings
$ Location: Time Zone Meridian in U.S. (Springfield, IL)
$
$ Ground temperatures were taken from Appendix A, NBSIR 81-2378, "Heat
$ Transfer Analysis of Underground Heat and Chilled-Water Distribution
$ Systems".

$ 1-Day design data - COOLING.
$
RC(DEM/UIN=ENGLISH/UOUT=ENGLISH)
LOC(DESC='TIME ZONE MERIDIAN LONG 90, LAT 40'/LATD=40/LONG=90/TZ=6/ALT=587)
GRND(GRT=12*52.0)
DAY(DESC='24 TEMPERATURES'/DATE=21SEPT/CLR=1/CLD=24*0/TA=24*80)
$
```